AFRL-RX-TY-TR-2011-0101

EVALUATION OF SUPPRESSION OF HYDROPROCESSED RENEWABLE JET (HRJ) FUEL FIRES WITH AQUEOUS FILM FORMING FOAM (AFFF)

Steven P. Wells
Applied Research Associates
PO Box 40128
Tyndall Air Force Base, FL 32403

Brent M. Pickett and Howard T. Mayfield
Air Force Research Laboratory
139 Barnes Drive, Suite 2
Tyndall Air Force Base, FL 32403-5323

Contract No. FA4819-09-C-0030

July 2011

.

DISTRIBUTION A: Approved for public release; distribution unlimited.
88ABW-2011-6612, 27 December 2011

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE

■ **Air Force Materiel Command** ■ **United States Air Force** ■ **Tyndall Air Force Base, FL 32403-5323**

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the 325th Fighter Wing Public Affairs Office at Tyndall Air Force Base, Florida and is available to the general public, including foreign nationals. Copies may be obtained from the Defense Technical Information Center (DTIC) (http://www.dtic.mil).

AFRL-RX-TY-TR-2011-0101 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

WALKER.KRYSTAL.MARIE.1123581462
Digitally signed by WALKER.KRYSTAL.MARIE.1123581462
DN: c=US, o=U.S. Government, ou=DoD, ou=PKI, ou=USAF, cn=WALKER.KRYSTAL.MARIE.1123581462
Date: 2011.12.12 15:02:13 -06'00'

KRYSTAL M. WALKER, Capt, USAF
Work Unit Manager

SKIBBA.BRIAN.K.1263420981
Digitally signed by SKIBBA.BRIAN.K.1263420981
DN: c=US, o=U.S. Government, ou=DoD, ou=PKI, ou=USAF, cn=SKIBBA.BRIAN.K.1263420981
Date: 2011.12.09 15:38:13 -06'00'

BRIAN K. SKIBBA, DR-III
Acting Chief, Airbase Engineering Development Branch

PILSON.DONNA.L.1186939324
Digitally signed by PILSON.DONNA.L.1186939324
DN: c=US, o=U.S. Government, ou=DoD, ou=PKI, ou=USAF, cn=PILSON.DONNA.L.1186939324
Date: 2012.01.03 13:25:38 -06'00'

DONNA L. PILSON, LtCol, USAF
Chief, Airbase Technologies Division

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
27-JUL-2011	Technical Report	30-JUL-2010 -- 30-JUL-2011

4. TITLE AND SUBTITLE

Evaluation of Suppression of Hydroprocessed Renewable Jet (HRJ) Fuel Fires with Aqueous Film Forming Foam (AFFF)

5a. CONTRACT NUMBER
FA4819-09-C-0030

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
0602102F

6. AUTHOR(S)
*Wells, Steven P.; **Pickett, Brent M.; **Mayfield, Howard T.

5d. PROJECT NUMBER
4915

5e. TASK NUMBER
D0

5f. WORK UNIT NUMBER
QD103001

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

*Applied Research Associates
PO Box 40128
Tyndall AFB, FL 32403

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

**Air Force Research Laboratory
Materials and Manufacturing Directorate
Airbase Technologies Division
139 Barnes Drive, Suite 2
Tyndall Air Force Base, FL 32403-5323

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RXQES

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RX-TY-TR-2011-0101

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION A: Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

Ref Public Affairs Case # 88ABW-2011-6612, 27 December 2011. Document contains color images.

14. ABSTRACT

Bio-oil derived hydroprocessed renewable jet (HRJ) fuels are alternative fuels that are being evaluated for use in United States Air Force (USAF) aircraft and support equipment and vehicles (SE&V). As with any new weapons system or other type of potential fire threat, the fire protection safety risk to the first responder must be established. This program was designed to determine if Military Specification MIL-F-24385F (MIL-SPEC) Aqueous Film Forming Foam (AFFF) has the capability of extinguishing HRJ fuel fires and HRJ/JP-8 blended fuel fires. The assessment included extinguishment effectiveness, extinguishment time, and burn-back time. Heat flux was also measured for six-foot pan fires with HRJ and synthetic alternative fuels and fuel blends. Jet fuels evaluated in this program were conventional JP-8 fuel (specified by MIL-DTL-83133F), two HRJ fuels produced by UOP LLC, a Synthetic Paraffinic Kerosene (SPK) fuel produced by Syntroleum Corporation (S-8) and a synthetic fuel produced by Shell (FT-IPK).

15. SUBJECT TERMS

hydroprocessed renewable jet fuel, HRJ, fire suppression, AFFF, alternative fuel, JP-8, Synthetic Paraffinic Kerosene (SPK)

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Shaun O'Bryant
U	U	U	UU	51	19b. TELEPHONE NUMBER *(Include area code)*

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

TABLE OF CONTENTS

LIST OF FIGURES ii
LIST OF TABLES iii
1. SUMMARY 1
1.1. Background 1
1.2. Scope 1
1.3. Conclusions and Recommendations 1
2. INTRODUCTION 2
2.1. Scope 2
2.2. Fuels Tested 2
3. METHODS, ASSUMPTIONS, AND PROCEDURES 4
3.1. Fuel Properties 4
3.2. Pool Fire Flame Temperature and Emissions Measurements 4
3.2.1. Pool Fire Evaluations 4
3.2.2. Camera Images 5
3.2.3. Video Images 7
3.3. Fire Suppression Experiments 7
3.3.1. Instrumentation 7
3.3.2. Test Pans 7
3.3.3. Extinguisher and Nozzle 7
3.3.4. Firefighting Agent 7
3.3.5. Fuels Tested 8
3.3.6. Fire Evaluation Procedures 8
4. RESULTS AND DISCUSSION 9
4.1. Fuel Properties 9
4.2. Pool Fire Flame Temperature and Emissions Measurements 9
4.2.1. Pool Fire Evaluations 9
4.2.2. Camera Images 13
4.2.3. Video Images 15
4.3. Fire Suppression Experiments 16
4.3.1. Conventional JP-8 Fuel 17
4.3.2. HRJ and Blended Jet Fuels 17
4.3.3. Pre-burn and Burn-back 18
5. CONCLUSIONS AND RECOMMENDATIONS 21
6. REFERENCES 22
Appendix A: MATLAB Routine 23
Appendix B: Unsuppressed Fuel Fire Data 24
LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS 48

Distribution A: Approved for public release; distribution unlimited.

LIST OF FIGURES

Page

Figure 1. Fire Hangar at Tyndall Air Force Base 4
Figure 2. Six-ft Test Pan and Instrumentation 5
Figure 3. Section Analyzed of Unsuppressed Fire (a) Original Image, (b) Cropped Image, (c) Binary Image of 0.5 Luminosity Threshold 6
Figure 4. Tri-Max 30 Extinguisher 7
Figure 5. Camelina Unsuppressed Fire Test 9
Figure 6. Camelina HRJ Test 16-5 Temperatures 10
Figure 7. Unsuppressed Gasoline Test 14-1 Sensor 2 Heat Flux 11
Figure 8. Camelina HRJ/JP-8 50/50 Test 16-3 Sensor 2 Heat Flux 11
Figure 9. Sensor 2 Average Heat Flux (with 95% Confidence Intervals) 12
Figure 10. Percentage of Dark/Smoky Flame by Image Analysis (with 95% Confidence Intervals) 13
Figure 11. Photographs of Fully Involved 6-ft Diameter Fuel Fires 14
Figure 12. Underwater Video Screen Capture of a JP-8 Fire 15
Figure 13. Underwater Video Screen Capture of a Tallow Fire 15
Figure 14. Foam Layer Advancing from Lower Left to Upper Right 15
Figure 15. Average Extinguishment Times (with 95% Confidence Intervals) for Five Fuels 19
Figure 16. Average Burn-back Times (with 95% Confidence Intervals) for Five Fuels 19
Figure 17. Sensor 2 Heat Flux during Camelina Fire Suppression and Unsuppressed Evaluations 20

Distribution A: Approved for public release; distribution unlimited.

LIST OF TABLES

Page

Table 1. Fuel Manufacturers and Flash Points 3
Table 2. Measured Density and Flash Point 9
Table 3. Time from Ignition to Reach Steady-State Heat Flux Levels 10
Table 4. Average Heat Flux during Steady-State Combustion 12
Table 5. Pre-burn, Extinguishment and Burn-back Times for JP-8 Fuel Fires 17
Table 6. Pre-burn, Extinguishment and Burn-back Times for HRJ Fuel Fires 17
Table 7. Pre-burn, Extinguishment and Burn-back Times for HRJ/JP-8 Blended Fuel Fires 18
Table 8. Average Pre-burn, Extinguishing and Burn-back Results 19

Distribution A: Approved for public release; distribution unlimited.

1. SUMMARY

1.1. Background

Alternative liquid jet fuels are being considered as a replacement for petroleum-based fuels by the United States Air Force (USAF). Bio-oil-derived hydroprocessed renewable jet (HRJ) fuels, also known as hydroprocessed esters and fatty acids (HEFA) fuels, are alternative fuels that are being evaluated for use in USAF aircraft and support equipment and vehicles (SE&V). Some synthetic paraffinic kerosene (SPK) alternative fuels have previously been certified for use in USAF aircraft and SE&V. In these evaluations, the alternative fuel is blended 50/50 with conventional Jet Propellent-8 (JP-8). As with any new weapons system or other type of potential fire threat, the fire protection safety risk to the first responder must be established. With the increased interest in alternative fuels, there are questions of whether existing aqueous film-forming foam (AFFF) firefighting agents and equipment are capable of extinguishing alternative-fuel fires or firefighters will need additional or new tools to successfully extinguish these fires. Testing was performed at the request of the Aeronautical Systems Center Alternative Fuels Certification Division (ASC/WNN).

1.2. Scope

This program was designed to determine if Military Specification MIL-F-24385F[1] (MIL-SPEC) AFFF is able to extinguish HRJ fuel fires and HRJ/ JP-8 blended fuel fires. The ability of existing military firefighting agents and techniques to suppress fuel and blended-fuel fires was evaluated . The assessment included extinguishment effectiveness, extinguishment time, and burn-back time. Heat flux was also measured for 6-ft pan fires with HRJ and synthetic alternative fuels and fuel blends.

Jet fuels evaluated in this program were conventional JP-8 fuel (specified by MIL-DTL-83133F), two HRJ fuels produced by UOP, LLC, a SPK fuel produced by Syntroleum Corporation (S-8) and a synthetic fuel produced by Shell (FT-IPK). Both SPK fuels were derived from a Fischer–Tropsch (F-T) process.

1.3. Conclusions and Recommendations

Test results show AFFF and existing firefighting equipment will extinguish the tested HRJ fuel fires just as effectively as conventional fuel fires. AFFF burn-back protection of the HRJ fuels and blends is comparable to that of JP-8. Radiant emissions from HRJ and JP-8 fires are similar. Higher heat flux was measured from SPK and SPK-blend fuels.

Firefighters and first responders should continue to use AFFF firefighting agent with these HRJ fuels as they would for fuel spill incidents involving JP-8. It is recommended that each additional new fuel undergo a minimum series of evaluations using the methods discussed in this report to ensure the safety of firefighters and the effectiveness of firefighting equipment and agents.

Distribution A: Approved for public release; distribution unlimited.

2. INTRODUCTION

Alternative liquid jet fuels are being considered as a replacement for petroleum-based fuels by the USAF. Bio-oil-derived HRJ fuels, also known as HEFA fuels, are alternative fuels that are being evaluated for use in USAF aircraft and SE&V. Some SPK alternative fuels have previously been certified for use in USAF aircraft and SE&V. In these evaluations, the alternative fuel is blended 50/50 with conventional JP-8. As with any new weapons system or other type of potential fire threat, the fire protection safety risk to the first responder must be established. With the increased interest in alternative fuels, there are questions of whether existing AFFF firefighting agents and equipment are capable of extinguishing alternative fuel fires or firefighters will need additional or new tools to successfully extinguish these fires. Testing was performed at the request of ASC/WNN.

AFFF is used by Air Force fire departments to extinguish fuel spill fires involving JP-8, diesel or gasoline. With the increased interest in alternative fuels, there are questions of whether existing AFFF firefighting agents and equipment are capable of extinguishing alternative fuel fires or if firefighters will need additional or new tools to successfully extinguish these fires.

2.1. Scope

To aid Air Force firefighters' response to an incident involving alternative fuels, this program was designed to determine if MIL SPEC MIL-F-24385F[1] AFFF has the capability of extinguishing alternative-fuel fires and blended-fuel fires. This evaluation mostly followed parameters set forth in the MIL-SPEC guidelines, MIL-F-24385F, Section 4.7.13 for a 28-ft^2 fire test. The ability of existing military firefighting agents and techniques to suppress fuel and blended-fuel fires was evaluated. The assessment included extinguishment effectiveness, extinguishment time and burn-back time, as well as relative heat flux values from these fires and qualitative information comparing smoke production from these alternative fuels and from JP-8.

2.2. Fuels Tested

Fire tests were performed on various kerosene-based jet fuels including the conventional JP-8 fuel (MIL-DTL-83133F) that is currently used by the Air Force and two bio-oil derived HRJ fuels: Camelina and Tallow. The HRJ fuels were produced by UOP, LLC, which is a Honeywell company. In addition to these, some fuels were also evaluated for radiation emissions: unleaded gasoline and two SPK jet fuels; one produced by Syntroleum Corporation (S-8) and one produced by Shell (FT-IPK). The alternative fuels were evaluated in the neat form and mixed 50/50 by volume with JP-8 as it is used in aircraft operations. Fire suppression characteristics of SPK fuels were evaluated previously[2]. Conventional JP-8 was used as a baseline to which all other fuels were compared.

The flash point of a liquid is the lowest temperature at which its flammable vapors will ignite when an ignition source is applied. It is one indicator of the overall flammability of the fuel. Those fuels with higher flash points are less volatile. Fuels that are below their flash point require an ignition source that provides local heating to increase their temperature before ignition occurs. Fuels below their flash point temperature typically take longer to ignite and burn than

Distribution A: Approved for public release; distribution unlimited.

fuels that are above their flash points. The flash points found in the manufacturer's MSDS for these various fuels are shown in Table 1.

Table 1. Fuel Manufacturers and Flash Points

Fuel	Manufacturer	Flash Point
Conventional Jet Fuel (JP-8)	Shell Oil Products/ Mobil	> 100 °F (> 38 °C)
Camelina HRJ	UOP LLC	> 100 °F (> 38 °C)
Tallow HRJ	UOP LLC	> 100 °F (> 38 °C)
Synthetic JP-8 (FT-IPK)	Shell Oil Products	100 °F (38 °C)
Synthetic JP-8 (S-8)	Syntroleum Corporation	100–125 °F (37.8–51.5 °C)
Unleaded Gasoline		-45 °F (-43 °C)

Distribution A: Approved for public release; distribution unlimited.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

All of the 6-ft pan fuel fire evaluations were conducted in the Fire Hangar at AFRL Test Range II, Tyndall AFB, FL. The Fire Hangar building is 88 ft × 80 ft with a maximum height of 32 ft (Figure 1). This facility provides an indoor fire test environment conducive to repeatable results and eliminates the impact of adverse weather conditions on the fire. All evaluations were performed with the hangar doors closed to eliminate the effect of air currents on the fires.

Figure 1. Fire Hangar at Tyndall Air Force Base

3.1. Fuel Properties

The fuel flash point test was conducted per ASTM D93-07 "Standard Test Methods for Flash Point by Pensky–Martens Closed Cup Tester"[3]. Density of the fuels was measured at room temperature using a Mettler Toledo Densito 30PX instrument.

3.2. Pool Fire Flame Temperature and Emissions Measurements

3.2.1. Pool Fire Evaluations

Radiant heat flux and flame temperatures were recorded from fuel fires in a 6-ft diameter pan. Water was placed into the pan to a depth of 0.5 in (more water than normal was used to ensure that an underwater camera was submerged). Ten gal of fuel was then added into the pan. The fuel was ignited with a propane torch and allowed to burn unsuppressed until the fires reached a steady-state condition that was indicated when heat flux measurements ceased to increase. This heat flux level varied from test to test. The fires were allowed to burn freely for approximately 100 s more and then were suppressed either by using AFFF or by capping the pan. The pan was emptied and cooled between tests.

Two experiments each were conducted with JP-8, Camelina HRJ, Tallow HRJ, and each HRJ fuel blend (Camelina HRJ/JP-8 50/50 and Tallow HRJ/JP-8 50/50). One experiment each was conducted with FT-IPK, S-8, and SPK fuel blends (FT-IPK /JP-8 50/50, and S-8/JP-8 50/50).

Two thermocouples were installed 3 ft and 6 ft above the fuel surface in the center of the test pan to record flame temperatures. The thermocouples were 1/16-in stainless steel, sheathed, ungrounded, type k with a response time of 6 s. Two additional thermocouples were installed adjacent to the heat flux sensors. Heat flux was recorded at two locations adjacent to the test pan.

Distribution A: Approved for public release; distribution unlimited.

Sensor 1 was a Medtherm 96-30T-30RP(ZnSe)-120-21746, Schmidt–Boelter heat flux transducer (center of Figure 2) installed at the edge of the test pan, 3 ft above fuel surface and 3 ft from the center of the pan facing the center of the pan. Sensor 2 was a Medtherm GTW-7-32-485A, Schmidt–Boelter heat flux transducer (far right of Figure 2) installed 3 ft above the fuel surface and 11 ft from the center of the pan facing the center of the pan. Thermocouples and heat flux sensors were placed such that they would not interfere with fire suppression operations.

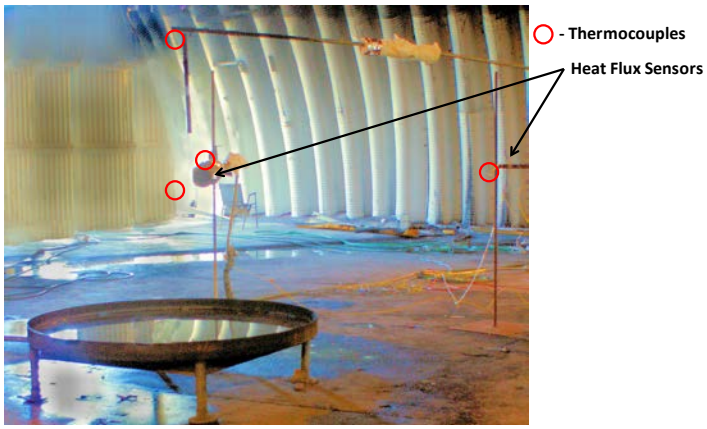


Figure 2. Six-ft Test Pan and Instrumentation

Before testing was conducted, estimates were calculated of the approximate heat flux expected at the two sensor locations to ensure appropriate sensors were specified. These estimates were based on a method by Shokri and Beyler[4] for preliminary assessment of thermal radiation from liquid hydrocarbon fuel pool fires. They developed the following general formula,

$$\dot{q}'' = 15.4\,(\frac{L}{D})^{-1.59}\ (\mathrm{kW/m^2}) \qquad (1)$$

where L is the distance from the center of the fire and D is the diameter of the circular pool fire. The formula calculates values at the base of the fire and does not take into account height. Using this formula, radiation for heat flux sensor 1, at the edge of the pan, was calculated to be 46 kW/m^2. Radiation at sensor 2, 8 ft away from the pan, was calculated to be 5.9 kW/m^2. As the sensors used in these tests were located 3 ft higher than the base of the fire, it was also expected that measurements could exceed these calculated values because more flame is radiated at this sensor location due to the enlarged view factor. A safety factor of two (2) is sometimes used[5] with Equation 1.

National Instruments PXI/SCXI data acquisition hardware was used to record the data. Labview software was used to record data at 1 Hz. Two video cameras were installed around the test pan and an underwater GoPro® video camera recorded the fire from below the layer of fuel.

3.2.2. Camera Images

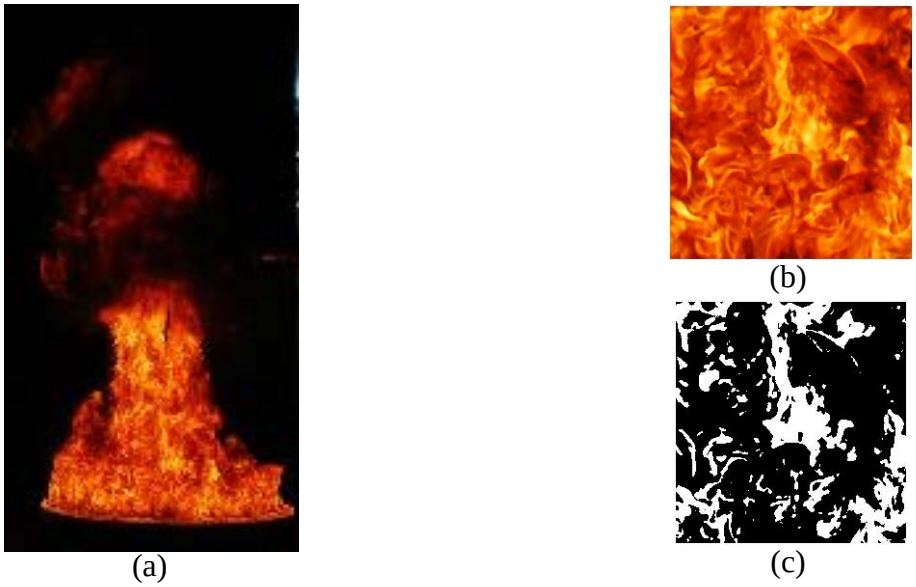
A Nikon D60 camera was used to record still images of the fires and the fire plumes. The camera was set to a manual mode, f-stop 4.0 and shutter 1/400 s. Images of the pan fires were recorded as color images in the Joint Photographic Experts Group (jpg) standard format. These still

Distribution A: Approved for public release; distribution unlimited.

images were captured at random times after it appeared the fire had reached full involvement. An attempt was made to locate the camera in the same place with the same field of view and camera settings for each test. The images were collected to document any visual differences in the appearance of the fires from different fuels. Additional post analysis of the images included analyzing a section of each image for relative pixel brightness for each fuel, intended as an indication of the smoke production and obscuration from fires from each fuel type.

The image analysis system used was MATLAB®, version 7.11, and the Image Analysis Toolbox™ version 7.1. The "bwarea" function analyzes binary (pure black-and-white) images to indicate the number of white pixels present in a binary image. Using this capability required converting the image from its full-color jpg form into a binary image using the "im2bw" routine. The "im2bw" routine converts color images into binary images using a threshold value of luminosity, ranging from 0–1; 0.5 luminosity was selected for this analysis. The routine converted the original color image into a grayscale image, and pixels of the converted image with luminosities exceeding the threshold value were assigned a value of 1 in the derived binary image.[6]

Conversion of the entire fire image and analysis of the dark areas was not feasible due to extraneous picture elements—the images included the fires and background. Instead the "imcrop" routine was used to crop a rectangular element from each fire image (as depicted in Figure 3), and that rectangular section of flame was analyzed for darker and brighter elements as described above. An initial attempt to set a standard rectangular frame for all images failed, as movement of the camera or wind blowing on some of the flames shifted too many of the images out of the frame. Instead the image was displayed and the MATLAB® user selected a frame for each image, and the elements of the selected rectangle were reported along with other results from the image. The area for the selected cropping frame of each image was calculated from the width and height of the rectangle. Sections of six images from each fuel fire were analyzed and the fraction of the rectangular flame section which was light was calculated, and the dark fraction was obtained as the complement. The MATLAB® script is listed in Appendix A.



(a) (b) (c)

Figure 3. Section Analyzed of Unsuppressed Fire (a) Original Image, (b) Cropped Image, (c) Binary Image of 0.5 Luminosity Threshold

Distribution A: Approved for public release; distribution unlimited.

3.2.3. Video Images

A GoPro video camera with a wide angle lens recorded the tests from inside the test pan, underneath the fuel layer. The purpose of this video recording was to evaluate if any additional properties of the fire extinguishing agent or the fuel combustion could be determined.

3.3. Fire Suppression Experiments

The following sections describe equipment and procedures used for fire suppression experiments. Additional illustrations of the equipment and procedures were included in AFRL-RX-TY-TR-2009-4510.

3.3.1. Instrumentation

The instrumentation described in Section 3.2 was also used to record data during fire suppression experiments. The Nikon D60 camera and the GoPro® video camera were not used for fire suppression experiments.

3.3.2. Test Pans

Two ¼-in thick stainless steel test pans were used for fire tests: a 6-ft diameter (28-ft^2) pan with a 4-in high side and a 1-ft diameter burn-back pan with a 2-in high side. The pans were fabricated as specified in MIL-F-24385F.

3.3.3. Extinguisher and Nozzle

To ensure a consistent 100-psi nozzle pressure with a 2-gal/min (gpm) flow rate, a 30-gal volume extinguisher was used as a pressure vessel attached to a self-generating nitrogen servicing cart. The Tri-Max 30 fire extinguisher shown in Figure 4 was modified for these tests so that air was not injected into the agent discharge line as is typical for this extinguisher. The pressure at the nozzle was verified before each test and the agent flow rate verification was performed after every two tests to ensure consistency in testing. A 50-ft, 1-in diameter hose was connected between the extinguisher and the nozzle, which was fabricated as specified in MIL-F-24385F

Figure 4. Tri-Max 30 Extinguisher

3.3.4. Firefighting Agent

Chemguard 3% qualified products list (QPL-24385-26) MIL-SPEC AFFF was used as the firefighting agent in all tests. To eliminate the fire suppression agent as a variable in these evaluations, the agent and the concentration that the agent was mixed with water (3%) did not vary throughout the testing.

Distribution A: Approved for public release; distribution unlimited.

3.3.5. Fuels Tested

Five experiments each were conducted with JP-8, Camelina HRJ, Tallow HRJ, and each HRJ fuel blend (Camelina HRJ/JP-8 50/50 and Tallow HRJ/JP-8 50/50).

3.3.6. Fire Evaluation Procedures

Medium-scale evaluations followed the procedures in MIL-F-24385F, Section 4.7.13 for a 28-ft^2 fire test with the exception of pre-burn times. Pre-burn times varied as explained below. For consistency, the same firefighter fought all of the fires, following a similar pattern each time. The fuels were tested in random order.

A shallow layer of fresh water, approximately 0.25-in deep, was dispensed in the bottom of the 6-ft diameter pan to guarantee complete coverage of the area with fuel and to protect the pan's bottom. The pan was allowed to cool before each experiment. Ten gal of fuel were poured into the 28-ft^2 pan to provide an approximate 0.5-in fuel layer. The quantity of fuel specified ensures that results will not be affected by all of the fuel being consumed during the test. Within 30 s of pouring, the fuel was ignited.

The pre-burn for this type of test with unleaded gasoline is typically 10 s before the firefighter is permitted to attack the fire. Pre-burn is measured from fuel ignition until agent is applied to the fire. With unleaded gasoline, 10 s is sufficient for the fuel in the test pan to be considered fully involved in flames. Due to the lower volatility of the fuels evaluated in this test series, a different method was devised to ensure a fully involved fire each test.

After ignition, the fuel was allowed to burn freely until the flames spread across the pan and exhibited pulsing behavior, or puffing. At this time, flame heights were observed to exceed 15 ft for each evaluation. The test director allowed the fire to burn for an additional 5 s before instructing the firefighter to attack the fire. With this pre-burn method, the total time from ignition to full involvement may vary from test to test for reasons such as initial fuel temperature, flash points, or how long the ignition source is applied to the fuel. By ensuring a fully involved fire before beginning agent application, these variations were not significant and consistent extinguishment and burn-back results were assured.

After the pre-burn, the fire was "attacked and extinguished as expeditiously as possible" (MIL-F-24385F), with AFFF first applied from a fixed position of approximately 3 ft (1 m) from the perimeter of the pool fire so that the foam landed in the middle to back side of the fuel pan. After approximately 12 s, the firefighter moved to the opposite side of the pan and applied foam to any sections of the pan to quickly extinguish the fire. The moment of extinguishment was recorded and foam application continued for a total of 90 s, which ensured a consistent agent volume of 3 gal was used in each test. Within 60 s of completion of foam application, the 1-ft diameter pan containing flaming unleaded fuel was placed in the center of the 6-ft diameter pan to begin the burn-back portion of the evaluation. This portion of the test provides information on the relative safety of a fuel spill that is covered by a foam blanket. When the fire had spread outside the small pan and was burning steadily, the small pan was removed. The burn-back time was recorded when 7 ft^2 (25 percent) of the total area was covered in flames as determined by the test manager. The resulting fire was then suppressed.

Distribution A: Approved for public release; distribution unlimited.

4. RESULTS AND DISCUSSION

4.1. Fuel Properties

Both samples were tested for flash point and density. Table 2 shows densities and flash points of each fuel measured in the laboratory along with the MSDS values. Both the densities and flash points were comparable to the MSDS values.

Table 2. Measured Density and Flash Point

Fuel	Measured Density @ 15 °C	MSDS Reported Density	Measured Flash Point (ASTM D93-07)	MSDS Reported Flash Point
Camelina HRJ	0.751 g/cm^3	0.75–0.80 g/cm^3	41 °C	> 38 °C
Tallow HRJ	0.757 g/cm^3	0.75–0.80 g/cm^3	50 °C	> 38 °C

4.2. Pool Fire Flame Temperature and Emissions Measurements

4.2.1. Pool Fire Evaluations

Two evaluations each of gasoline, JP-8, HRJ fuels, and HRJ fuel/JP-8 blend were conducted. One test each was also conducted with FT-IPK and S-8. Each of the fires was allowed to burn unsuppressed at steady state for approximately 100 s before being extinguished. Two thermocouples were installed 3 ft and 6 ft above the fuel surface and thermocouples were installed adjacent to the heat flux sensors. Heat flux was recorded at two locations adjacent to the test pan as described in Section 3.2. Figure 5 shows the second Camelina unsuppressed fire test.

Figure 5. Camelina Unsuppressed Fire Test

The thermocouple installed 6 ft above the fuel surface measured temperatures ranging from 400 °C up to 1000 °C during steady-state combustion. The thermocouple installed 3 ft above the fuel surface measured temperatures ranging from 500 °C to 1050 °C during steady-state combustion. During most of the tests temperatures measured at each location reached 900 °C at

Distribution A: Approved for public release; distribution unlimited.

some point during the test, with the exception of the Camelina HRJ/JP-8 50/50 tests and the S-8 test. A representative data plot is shown in Figure 6. The temperature readings are affected by the response time of the sheathed thermocouple, and if flames were in contact with or adjacent to the point sensor. In some tests the flames were not always vertical, which kept flame temperatures away from the sensor and affected this measurement.

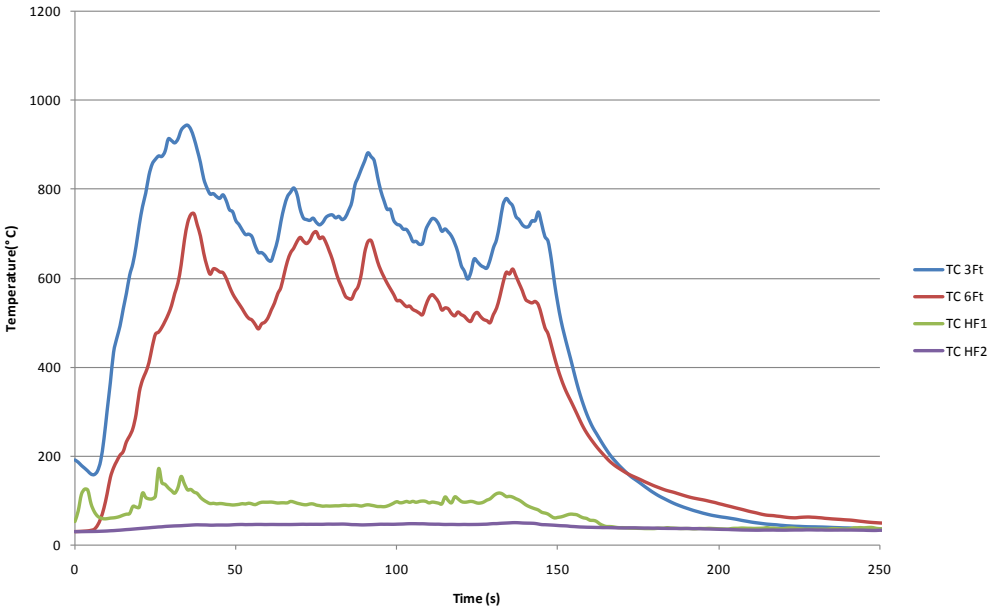


Figure 6. Camelina HRJ Test 16-5 Temperatures

Table 3 shows the time from fuel ignition until heat flux measurements stopped increasing and reached a steady output. For gasoline fires, this happened rapidly (4–11 s) because the fuel was well above its flash point when ignited. For all other fuels that were initially below their flash points, the heat from the fires took longer to reach maximum output (16–30 s). These measurements are similar to pre-burn times measured during fire suppression evaluations, which ranged

Table 3. Time from Ignition to Reach Steady-State Heat Flux Levels

			Time from Ignition (s)			
Fuel	**Test #**		**Sensor 1**		**Sensor 2**	
	Test 1	**Test 2**	**Test 1**	**Test 2**	**Test 1**	**Test 2**
Unleaded Gasoline	14-1	15-1	4	4	10	11
JP-8	15-2	16-4	25	22	25	24
Camelina HRJ	15-3	16-5	21	19	23	23
Camelina HRJ/JP-8 50/50	16-3	16-6	17	16	23	18
Tallow HRJ	16-1	16-8	26	26	28	32
Tallow HRJ /JP-8 50/50	16-2	16-7	23	19	28	25
FT-IPK	17-2	n/a	23	n/a	24	n/a
FT-IPK /JP-8 50/50	17-3	n/a	23	n/a	22	n/a
S-8	17-4	n/a	22	n/a	30	n/a
S-8 /JP-8 50/50	17-5	n/a	22	n/a	26	n/a

Distribution A: Approved for public release; distribution unlimited.

from 22–31 s. The pre-burn time data are presented in Sections 4.3.1– 4.3.3. Figure 7 and Figure 8 show heat flux data from a gasoline and a Camelina HRJ/JP-8 50/50 fire.

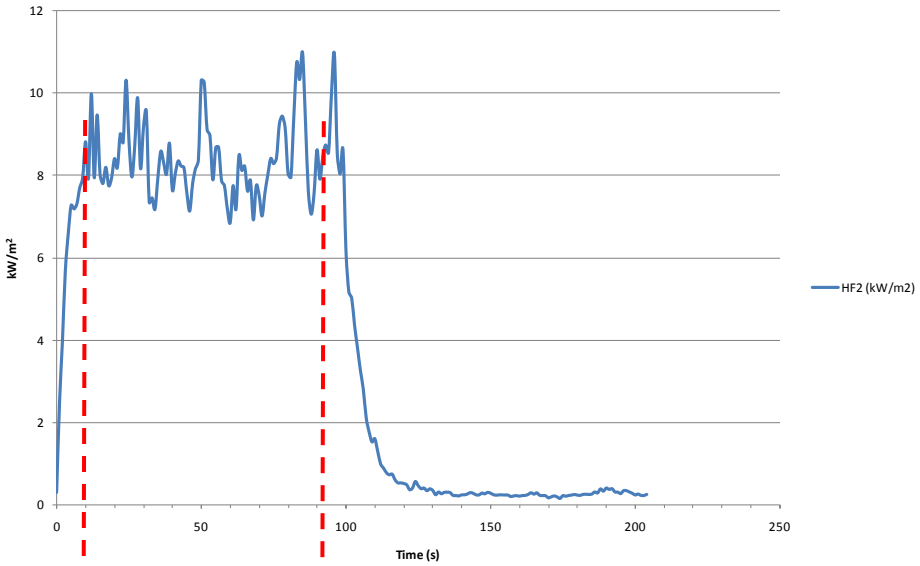


Figure 7. Unsuppressed Gasoline Test 14-1 Sensor 2 Heat Flux

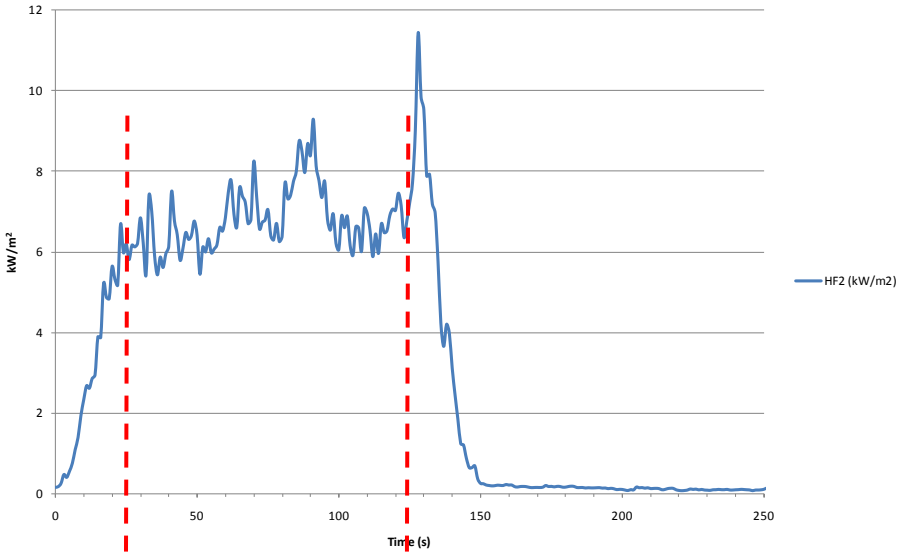


Figure 8. Camelina HRJ/JP-8 50/50 Test 16-3 Sensor 2 Heat Flux

Average measured heat flux values were calculated using sensor data starting 5 s after sensor 2 output began oscillating at steady-state levels and ending immediately before the fire was extinguished. The 5-s delay was added to ensure the heat flux output had stabilized. In Figure 7 and Figure 8 the dotted lines depict the data used to calculate average heat flux (the peak in the heat flux output in Figure 8 near the end of the test was due to fire extinguishing operations). Temperature and heat flux charts from all unsuppressed tests are located in Appendix B. Average heat flux results and standard deviations of the sensor data analyzed from all tests are listed in Table 4.

Distribution A: Approved for public release; distribution unlimited.

Table 4. Average Heat Flux during Steady-State Combustion

Fuel	Test #		Average Heat Flux (kW/m^2) & Standard Deviation (σ)							
			Sensor 1 (Radiometer)				Sensor 2 (Radiometer)			
			Test 1		Test 2		Test 1		Test 2	
	1	2	kW/m^2	σ	kW/m^2	σ	kW/m^2	σ	kW/m^2	σ
Unleaded Gasoline	14-1	15-1	18.0	6.06	42.0	4.85	8.39	0.93	9.09	0.86
JP-8	15-2	16-4	34.3	5.80	29.4	5.56	6.99	0.65	6.82	0.90
Camelina HRJ	15-3	16-5	21.4	4.11	35.5	3.98	7.10	0.67	6.78	0.57
Camelina HRJ/JP-8 50/50	16-3	16-6	38.0	5.24	29.1	5.18	6.79	0.78	7.28	1.46
Tallow HRJ	16-1	16-8	34.5	6.56	37.4	5.63	7.73	0.83	6.65	0.61
Tallow HRJ /JP-8 50/50	16-2	16-7	31.0	5.29	24.8	6.81	7.00	0.80	6.72	0.59
FT-IPK	17-2	n/a	31.6	4.61	n/a	n/a	7.76	0.71	n/a	n/a
FT-IPK /JP-8 50/50	17-3	n/a	44.2	10.5	n/a	n/a	7.90	0.97	n/a	n/a
S-8	17-4	n/a	36.9	5.73	n/a	n/a	7.51	0.77	n/a	n/a
S-8 /JP-8 50/50	17-5	n/a	30.5	8.89	n/a	n/a	7.74	0.84	n/a	n/a

For comparing fuel radiant emissions from test-to-test, the data from sensor 1 are less consistent than the sensor 2 data because sensor 2 was located further from the fire and was less susceptible to flame movement. Sensor 1 was located adjacent to the fire and when the flames leaned away from the sensor, the heat flux measurements dropped. On other occasions the flames leaned toward sensor 1 and engulfed the sensor causing the heat flux measurements to increase. The flame lean also affected sensor 2, but to a lesser degree than sensor 1. Sensor 2 data are plotted in Figure 9. Reviewing the results from sensor 2, the highest radiant emissions came from gasoline, the SPK fuels, and the SPK fuel blends. The heat flux measurements from JP-8, HRJ fuels and HRJ fuel blends were all similar and lower than the SPK fuels and gasoline.

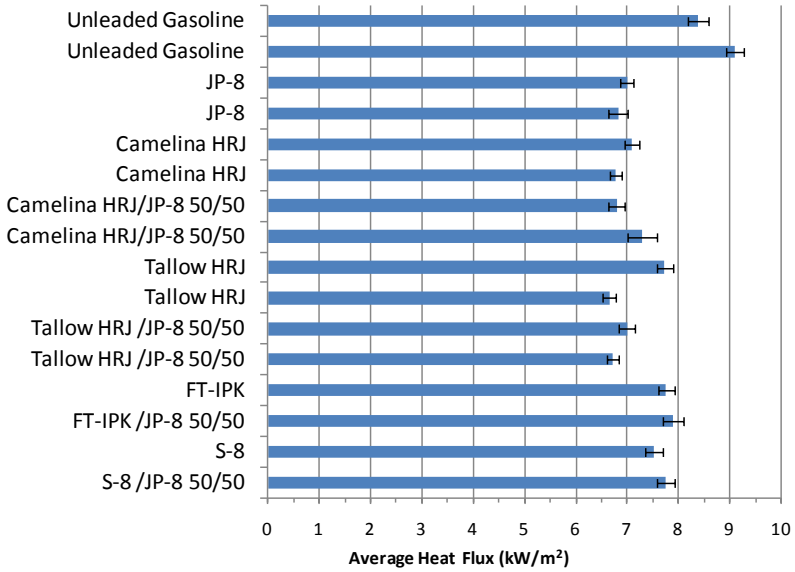


Figure 9. Sensor 2 Average Heat Flux (with 95% Confidence Intervals)

Distribution A: Approved for public release; distribution unlimited.

4.2.2. Camera Images

A Nikon D60 camera was used to record visible emissions from each of the fuels. The images collected show a representative scene of each fuel during steady state combustion. From a visual inspection of the images the fire brightness and colors varied with the fuel or fuel blends. The brightness of the flames is affected in part by the soot production in the fires. The effect of soot production in JP-8 and SPK fuels was discussed by Pickett *et al.*[7] For larger pool fires each fuel will have additional soot production due to incomplete fuel combustion, and flame brightness is expected to decrease as the pool size increases.[8]

To confirm visual observations, and as a crude measurement of the smoke production in the fires, a MATLAB® routine was used for a numerical analysis of the relative brightness of the flames. As described in Section 3.2.2, a subset of six images from each fuel were analyzed and the average area of pixels with luminosity exceeding 0.5 was calculated. The results from the image analysis of the fire images are presented in Figure 10 and a representative image from each fuel fire is shown in Figure 11. The data imply that JP-8 flames were darker than the neat alternative fuels indicating greater soot production by this fuel. The brightness of the 50/50 fuel blends falls in between that of JP-8 and neat alternative fuels.

The large error in Figure 10 indicates that the MATLAB® results are not completely reliable although the results did reinforce visual observations. The dynamic nature of the fires makes it difficult to obtain exact results from images that capture only a short duration of the entire event; however, it is possible that the reliability of these calculations may have been improved if additional photos were taken and were available for analysis. Smoke production was expected to vary during the course of the fire, an effect that was partially controlled by collecting the fire images when the fire was well involved. More rigorous quantification of the smoke produced could have been obtained by controlled air sampling from the fires and collection of the smoke

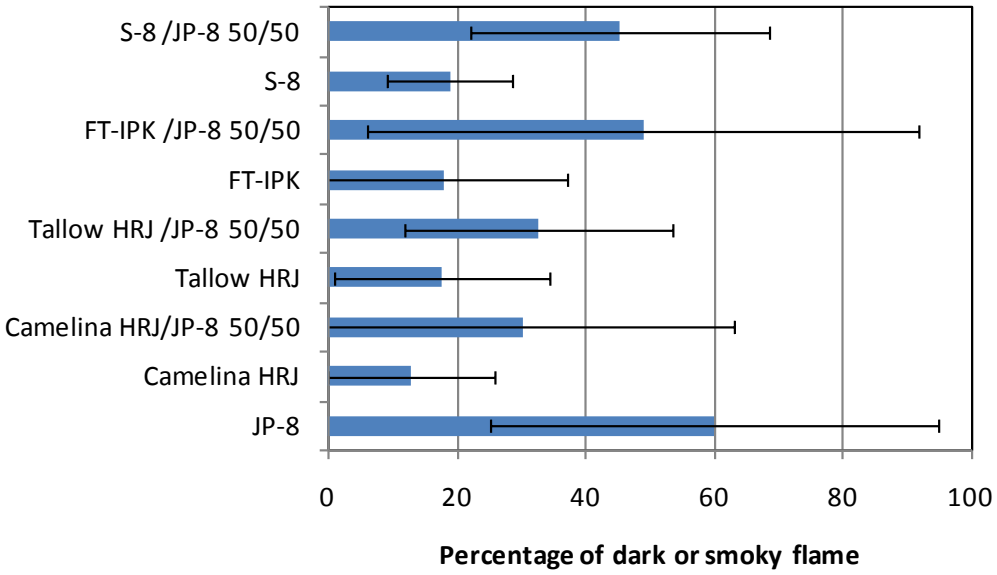


Figure 10. Percentage of Dark/Smoky Flame by Image Analysis (with 95% Confidence Intervals)

Distribution A: Approved for public release; distribution unlimited.

particles on filters. Filters, collected under quantitative conditions, can be analyzed with a mg-scale balance to indicate the mass of total particles collected from a given volume of air, or they can be analyzed visually to indicate the relative darkening of the filter and yield a "smoke number." Quantitative filter collection and mass measurement is a variation of the EPA Method 5, used to quantify particulates from smokestacks.[9] Collecting particles from an open pan fire would preclude the consideration of isokinetic sampling usually required in Method 5, but this would greatly simplify the procedure. The stack traverse considerations used in Method 5 for smokestack sampling would also require modification for an open flame sampling. The smoke number is a measurement from the Society of Automotive Engineers (SAE).[10] Either could be used for future experiments to produce more rigorous measurements of smoke from such fires.

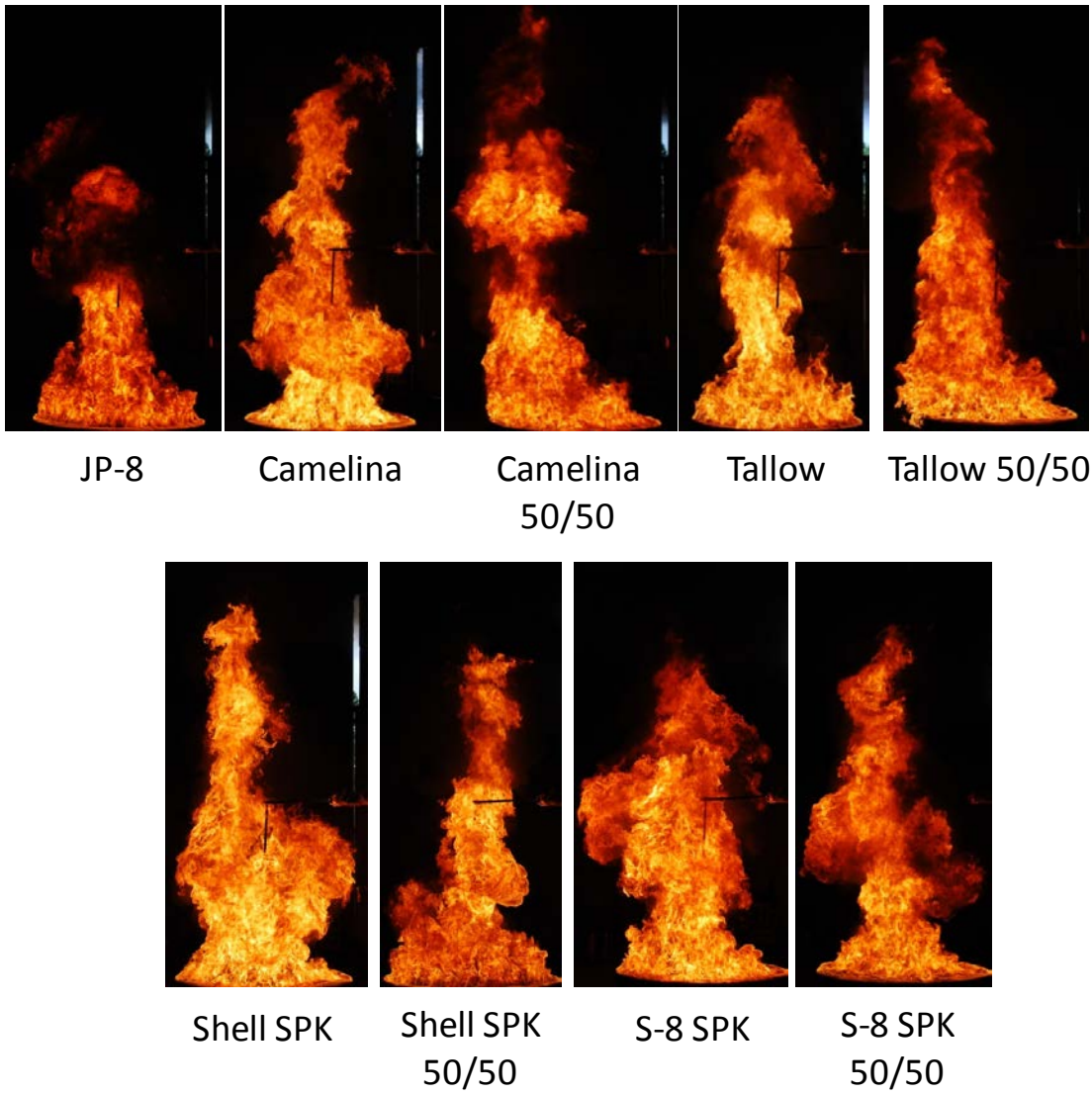
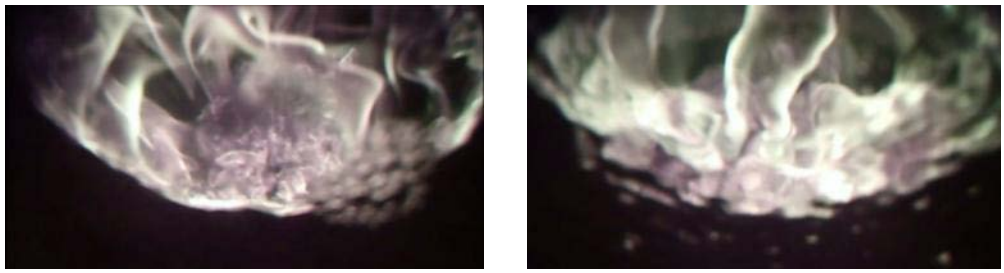


Figure 11. Photographs of Fully Involved 6-ft Diameter Fuel Fires

Distribution A: Approved for public release; distribution unlimited.

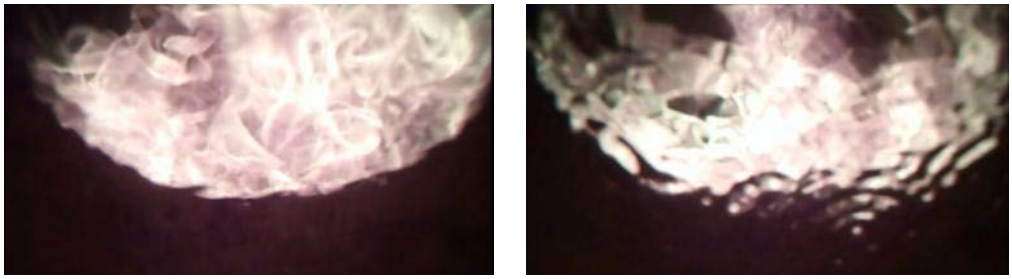
4.2.3. Video Images

Still frames from the underwater GoPro camera are shown in Figure 12–Figure 14. The wide-angle camera lens was able to capture more than half of the pool fire surface from below. In the figures, the curved transition from light to dark is the edge of the 6-ft diameter burn pan. Analysis of video revealed turbulence, increasing as the test progressed, created in the fuel layer during combustion. It also revealed what appeared to be boiling water that bubbled up through the fuel layer causing additional turbulence. Figure 12 shows frame captures from the test #16-4 JP-8 fire and Figure 13 shows frame captures from the test #16-8 Tallow HRJ fire. In the videos for all but the gasoline fuels, water bubbling up through the fuel began about 20–30 s after the



20 s after ignition 80 s after ignition

Figure 12. Underwater Video Screen Capture of a JP-8 Fire



20 s after ignition 80 s after ignition

Figure 13. Underwater Video Screen Capture of a Tallow Fire

Figure 14. Foam Layer Advancing from Lower Left to Upper Right

Distribution A: Approved for public release; distribution unlimited.

fuel was ignited. The bubbling and turbulence intensified 80–120 s after ignition, at which time the audio of the boiling also intensified. In all videos, soon after the fire suppression portion of the tests began, there was no more visible light beneath the liquid surface and the video went black. Figure 14 shows the layer of foam in test #16-1 as it first advances into the field of view. The foam is somewhat difficult to distinguish in the turbulent liquid.

4.3. Fire Suppression Experiments

Unleaded gasoline is typically used in this 6-ft diameter test pan to evaluate AFFF performance. MIL-F-24385F has the following specifications for an AFFF fire suppression test in the 28-ft^2 pan:

- Pre-burn Time: 10 s
- Extinguishing Time: 30 s
- 25 percent Burn-back Time: 6:00 min

The extinguishment time and burn-back time for JP-8 was compared to each fuel or fuel mixture by performing *t*-tests on the recorded data. The hypotheses tested were that the times to extinguish (t_{ex}) the alternative fuels and the burn-back times (t_{bb}) of the alternative fuels were no different than the times for JP-8 to a five percent level of significance. The *t*-test assumes that the samples have equal variance and follow a normal distribution. A *t*-statistic (*t*) is calculated by

$$t = \frac{\overline{X}_{\text{JP-8}} - \overline{X}_i}{\sigma_{X_{\text{JP-8}}X_i}\sqrt{1/n_{\text{JP-8}} + 1/n_i}} \tag{2a}$$

$$\sigma_{X_{\text{JP-8}}X_i} = \sqrt{\frac{(n_{\text{JP-8}} - 1)\sigma_{\text{JP-8}}^2 + (n_i - 1)\sigma_i^2}{DF}} \tag{2b}$$

$$DF = n_{\text{JP-8}} + n_i - 2 \tag{2c}$$

where the subscripts JP-8 and *i* represent the data sets for JP-8 and the comparison fuel (named *i* in Eq. 2), respectively. $\overline{X}$ is the average, σ is the standard deviation, and *n* is number of data points collected for the particular data set. $\sigma_{X_{\text{JP-8}}X_i}$ is a common standard deviation between the two fuel samples, and *DF* are the degrees of freedom for the two data sets. The probability is determined by a two-tailed normal distribution which is a function of *t* and *DF*.

$$p = f(t, DF) \tag{3}$$

If the probability resulting from that *t*-test was greater than 5%, the hypothesis was rejected, indicating that no difference in the extinguishment or burn-back times could be determined from the sample sets. The average values as well as confidence intervals (95%) were also determined. Figures showing these values will be discussed below in Section 4.3.2.

Distribution A: Approved for public release; distribution unlimited.

4.3.1. Conventional JP-8 Fuel

JP-8 was evaluated to establish a baseline for comparison with alternative fuels and conventional/alternative blended fuels. Table 5 shows the results from the JP-8 fires along with averages and 95 percent confidence intervals (CI). The mean pre-burn time to allow the JP-8 fires to become fully involved was 27.8 s. AFFF extinguished the JP-8 fires in an average time of 22.2 s and had a burn-back average time of 10 min 26 s.

In a previous study[2] to compare SPK results to JP-8, the baseline suppression and burn-back times for JP-8 fuel varied somewhat from the times measured here. A *t*-test analysis to a 95% confidence level verified that there was no significant difference in the JP-8 data between this and the previous study.

Table 5. Pre-burn, Extinguishment and Burn-back Times for JP-8 Fuel Fires

Test Number	Pre-burn Time (s)	Extinguishment Time (s)	25% Burn-back Time (min)
1	28	22	10:17
2	30	22	10:42
3	26	24	11:02
4	28	20	10:01
5	27	23	10:09
Average ± CI	27.8 ± 1.8	22.2 ± 1.8	10:26 ± 0:31

4.3.2. HRJ and Blended Jet Fuels

The Camelina HRJ alternative fuel required a pre-burn time mean of 27.0 s. The Tallow pre-burn average was 30.2 s. The Camelina and Tallow average extinguishment time were 23.8 and 23.2 s respectively. The burn-back averages were 10:36 and 10:19 respectively. Table 6 displays the results of the two HRJ fuels tested along with averages and 95 percent CI.

Table 6. Pre-burn, Extinguishment and Burn-back Times for HRJ Fuel Fires

HRJ Jet Fuel Tested	Pre-burn Time (s)	Extinguishment Time (s)	25% Burn-back Time (min)
Camelina	30	25	9:50
	31	23	11:18
	26	24	10:15
	25	25	9:54
	23	22	11:47
Average ± CI	27.0 ± 4.2	23.8 ± 1.6	10:36 ± 1:05
Tallow	31	24	11:30
	29	23	9:30
	31	21	10:21
	31	25	9:02
	29	23	11:12
Average ± CI	30.2 ± 1.4	23.2 ± 1.8	10:19 ± 1:18

Distribution A: Approved for public release; distribution unlimited.

The probabilities associated with *t*-tests for extinguishment times between JP-8 and the HRJ fuels were calculated as described in 4.3. Results indicated to a 95-percent confidence (five-percent level of significance) that AFFF can extinguish fires of both these HRJ fuels as quickly as JP-8. Similarly, burn-back times for Camelina and Tallow were not significantly different from JP-8. These results indicate that extinguishment by AFFF and burn-back safety of the HRJ fuels and JP-8 are similar.

The 50/50 mixture of HRJ and conventional JP-8 outcome was mostly consistent. The Camelina/JP-8 blend required an average 24.5-s pre-burn in order to have a fully engulfed fire, and the Tallow/JP-8 blend averaged 28.8 s. The Camelina/JP-8 blend extinguishment mean was 23 s and the Tallow/JP-8 blend mean was 22 s. The burn-back times also shared similarities. The Tallow/JP-8 blend had an average burn-back time of 10 min 22 s. The Camelina/JP-8 blend had an average burn-back time of 10 min 12 s. The results from the tested blends, averages, and 95 percent CI are listed in Table 7.

Table 7. Pre-burn, Extinguishment and Burn-back Times for HRJ/JP-8 Blended Fuel Fires

50/50 Blend Tested	Pre-burn Time (s)	Extinguishment Time (s)	25% Burn-back Time (min)
Camelina HRJ/JP-8	23	21	11:00
	29	26	9:20
	24	21	10:02
	26	30	10:10
	22	20	10:21
	23	20	10:22
Average ± CI	24.8 ± 3.4	23.0 ± 4.3	10:12 ± 0:34
Tallow HRJ/JP-8	30	24	10:26
	29	23	10:21
	31	20	10:29
	27	21	9:54
	27	22	10:41
Average ± CI	28.8 ± 2.2	22.0 ± 2.0	10:22 ± 0:21

t-Test comparisons of extinguishment time and burn-back time for JP-8 and each of the HRJ fuels and fuel blends indicated that AFFF performed as well on bio-fuels and blends as on JP-8.

Table 8 displays the average results of each fuel evaluated and 95 percent CI. The average for extinguishment and burn-back time as well as their CI are plotted in Figure 15 and Figure 16. The results show that AFFF is a very effective firefighting agent against HRJ fuel fires and that the performance of AFFF on HRJ fuel is similar to that on JP-8 fuel.

4.3.3. Pre-burn and Burn-back

An analysis of the test director's pre-burn and burn-back discretion was compared to measured heat flux data. The objective is to obtain a fully involved fire before beginning agent application. As an example, from Table 3, gasoline achieves steady state heat flux at the same time (10 s) that agent application initiation is required by MIL-F-24385F.

Distribution A: Approved for public release; distribution unlimited.

Table 8. Average Pre-burn, Extinguishing and Burn-back Results

Fuel	Average Pre-burn Time (s)	Average Extinguishing Time (s)	Average 25% Burn-back Time (min)
JP-8	27.8 ± 1.8	22.2 ± 1.8	10:26 ± 0:31
Camelina HRJ	27.0 ± 4.2	23.8 ± 1.6	10:36 ± 1:05
Camelina HRJ 50/50	24.8 ± 3.4	23.0 ± 4.3	10:12 ± 0:34
Tallow HRJ	30.2 ± 1.4	23.2 ± 1.8	10:19 ± 1:18
Tallow HRJ 50/50	28.8 ± 2.2	22.0 ± 2.0	10:22 ± 0:21

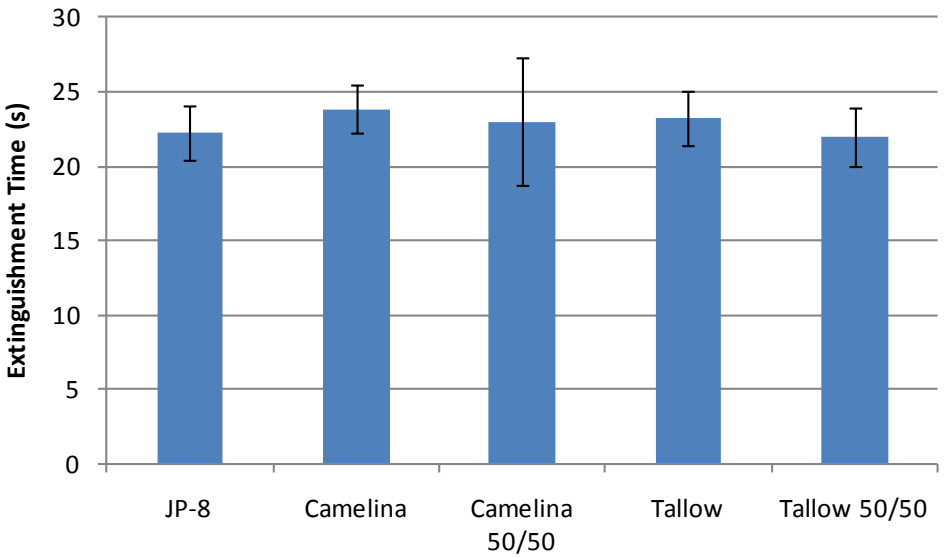


Figure 15. Average Extinguishment Times (with 95% Confidence Intervals) for Five Fuels

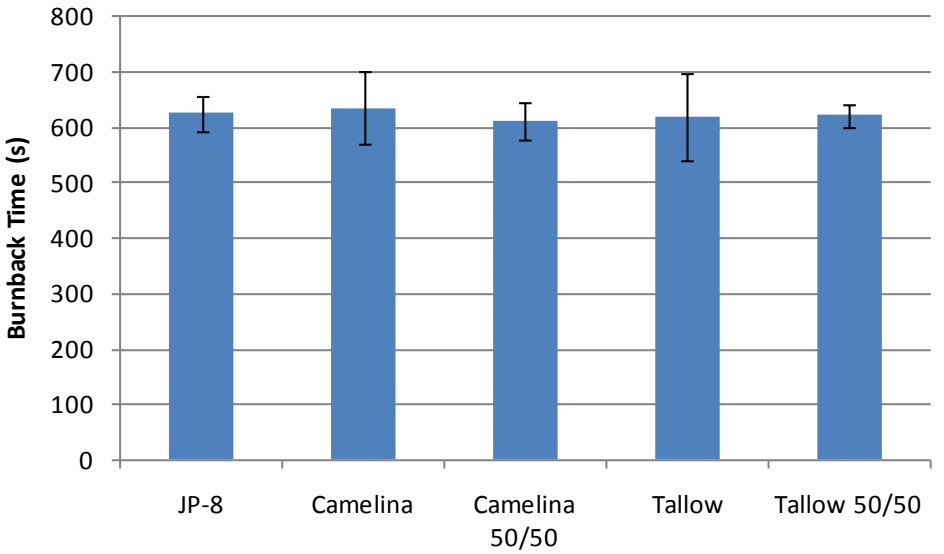


Figure 16. Average Burn-back Times (with 95% Confidence Intervals) for Five Fuels

Distribution A: Approved for public release; distribution unlimited.

Figure 17 shows data from one of the suppressed Camelina fire experiments and one of the unsuppressed Camelina fire experiments. Heat flux values for both experiments are equivalent until the time that fire suppression began, and steady-state heat flux level is achieved. Similar results were obtained for all fuels. Table 3 lists times from ignition of unsuppressed fires until sensor 2 indicated that steady state values had been reached (18–32 s). Likewise, pre-burn times during all fire suppression evaluations ranged from 22–31 s (Tables 6–8). The data collected indicate steady-state heat flux was achieved as the test director decided suppression should begin.

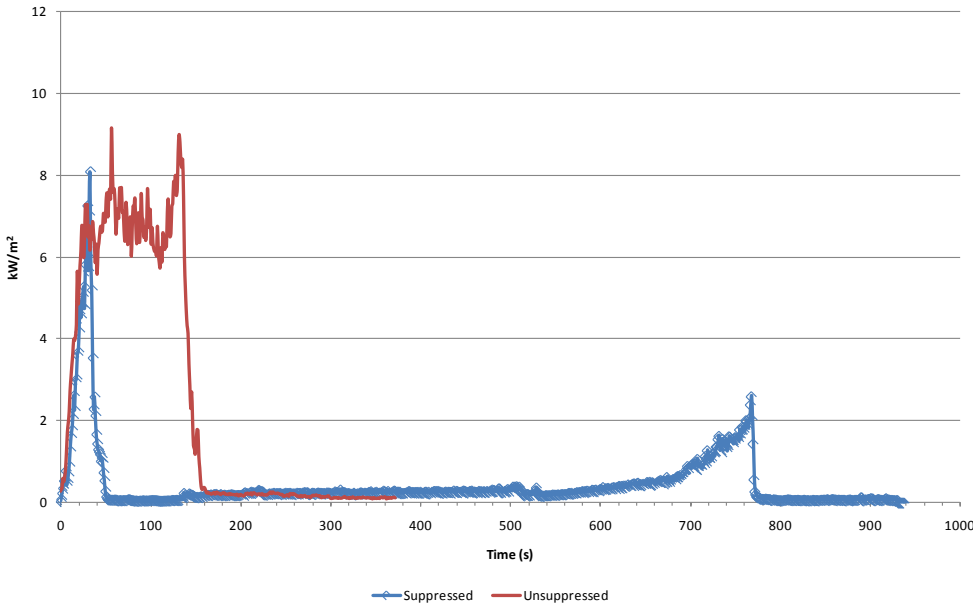


Figure 17. Sensor 2 Heat Flux during Camelina Fire Suppression and Unsuppressed Evaluations

Figure 17 also shows the increasing heat flux near the end of the suppressed experiment as the fire burns back. The peak at ~760 s is when the test director determined 25 percent burn-back. Similar heat flux results were obtained for all fuels. The heat flux measured at this time was approximately 25 percent of the unsuppressed steady state fire output, also indicating that the fire had burned back 25 percent. The test director's 25 percent burn-back determination results are also consistent with heat flux measurements.

Distribution A: Approved for public release; distribution unlimited.

5. CONCLUSIONS AND RECOMMENDATIONS

- Test results show AFFF and existing firefighting equipment will extinguish the tested HRJ fuel fires as effectively as conventional fuel fires. AFFF burn-back protection of the HRJ fuels and blends is also analogous to that of JP-8 fuel.
- Radiant emissions from HRJ fires are similar to JP-8. Higher heat flux was measured from SPK and SPK blend fuels.
- Video imaging from under the fuel surface did not reveal significant insights into fire suppression mechanisms.
- Either the test director's discretion (as described in this report) or measured heat flux can be utilized to determine 6-ft diameter pan fire pre-burn and burn-back times.

Firefighters and first responders should continue to use AFFF firefighting agent with these HRJ fuels as they would for fuel spill incidents involving JP-8. It is recommended that new fuels undergo a minimum series of evaluations using the methods discussed in this report to ensure the safety of firefighters and the effectiveness of firefighting equipment and agents.

Distribution A: Approved for public release; distribution unlimited.

6. REFERENCES

1) Military Specification, MIL-F-24385F. *Fire Extinguishing Agent, Aqueous Film-Forming Foam (AFFF) Liquid Concentrate, For Fresh and Sea Water*. 7 January 1992.

2) Burnette, Parren F ; Menchini, Christopher P ; Wells, Steven P ; Pickett, Brent M. *Evaluation of Suppression of Synthetic Paraffinic Kerosene (SPK) Fuel Fires with Aqueous Film Forming Foam (AFFF)*. December 2009. AFRL-RX-TY-TR-2009-4510.

3) ASTM D93-07, American Society for Testing and Materials. *Standard Test Methods for Flash Point by Pensky–Martens Closed Cup Tester*.

4) Shokri, M., Beyler, C.L., "Radiation from Larger Pool Fires." *SFPE Journal of Fire Protection Engineering*, 4, 1, pp.141–150. 1989.

5) Beyler, Craig L. "Fire Hazard Calculations for Large, Open Hydrocarbon Fires." *The SFPE Handbook of Fire Protection Engineering Third Edition*. 2002.

6) Image Processing Toolbox, Users Guide, R2010b, Mathworks Inc., Natick, MA, September 2010, current versions viewable at www.mathworks.com.

7) Pickett, Brent M.; Burnette, Parren F.; Wells, Steven P.; Sullivan, Patrick D.; Hawk. John R. "Fire safety tests comparing synthetic jet and diesel fuels with JP-8." *Fire Safety Journal* 46 (2011) 89–95.

8) Akita, K., and Kashio, T., *Study of Disaster*, 19:231 (1988) (in Japanese) cited in Qian, Cheng; Tashtoush, Ghassan; Ito, Akihiko; Saito, Kozo. "Structure of Large Scale Pool Fires". *International Conference on Fire Research and Engineering*, September,1995.

9) *Determination of Particulate Matter from Stationary Sources*, EPA Method 5, USEPA, downloaded from http://www.epa.gov/ttn/emc/promgate/m-05.pdf, accessed 4 Oct 2011, 15:41.

10) Aerospace Recommended Practice, ARP1179, *Aircraft Gas Turbine Engine Exhaust Smoke Measurement, Aerospace Recommended Practice, Rev. D*, SAE Aerospace, Warrendale, PA, Stabilized July 2011.

Distribution A: Approved for public release; distribution unlimited.

Appendix A: MATLAB Routine

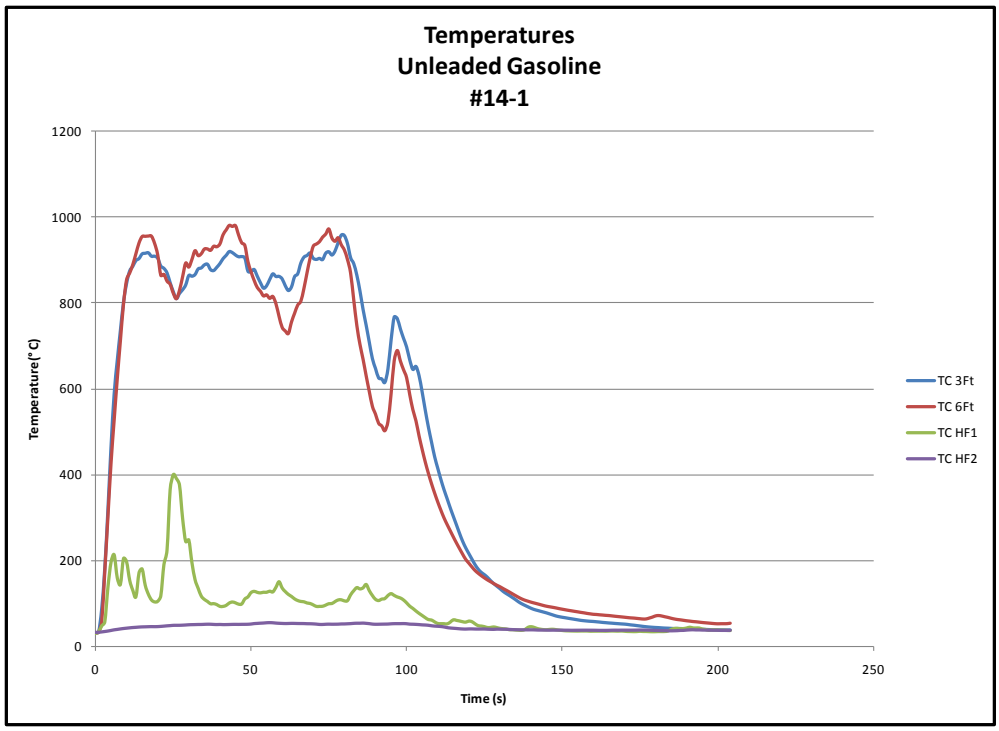
MATLAB script used to measure light and dark areas of flame images.

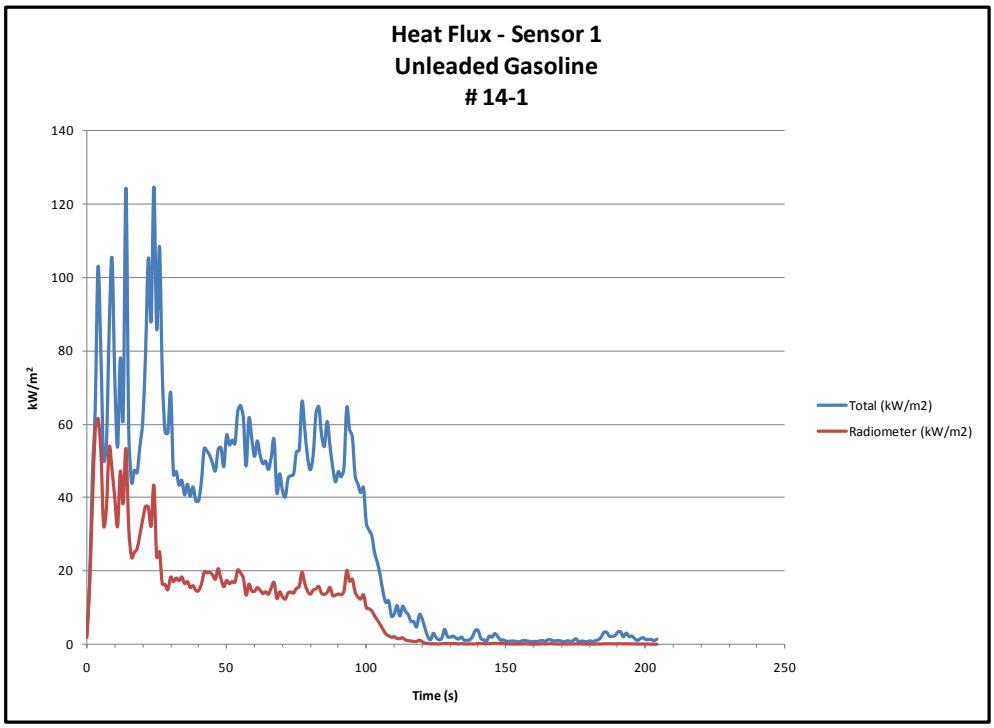
```
%M-File to crop a fixed rectangle from a flame photograph and then estimate
%the proportion of the rectangle that is darker flame, assumed to be sooty.
%The "darker" areas will be judged as areas with lower than 0.5 luminosity
%as termed in the MATLAB image analysis toolbox.

%Solicit a filename
[Filename,Pathname]=uigetfile('*.jpg','Load Fire Image');
FullFileName=[Pathname Filename];
RGB=imread(FullFileName);
imshow(RGB);
fprintf(1,'Flame Image File: %s\n',FullFileName);
%Get the standard rectangle area
%RectPath='F:\FireData\FuelFirePictures';
%RectFile='CropRect-Fire.mat';
%CropFullFileName=[RectPath '\' RectFile];
%eval load(CropFullFileName);
%FlameImg=imcrop(RGB,CropRect);
[FlameImg CropRect]=imcrop(RGB);
imshow(FlameImg)
BWFlame=im2bw(FlameImg,0.5);
FlameArea=bwarea(BWFlame);
CropSize=size(FlameImg);
CropArea=CropSize(1)*CropSize(2);
SmokeFrac=1-FlameArea/CropArea;
SmokePcnt=100*SmokeFrac;
%Report the percentage smoke
%fprintf(1,'Image \t\t Percent Smoky Flame\n');
%fprintf(1,'%s \t %8.4f\n',Filename,SmokePcnt);
fprintf(1,'Image \t\t Percent Smoky Flame \tCrop Rectangle\n');
fprintf(1,'%s \t %8.4f \t\t %10.4e %10.4e %10.4e
%10.4e\n',Filename,SmokePcnt,...
    CropRect(1:4));
```

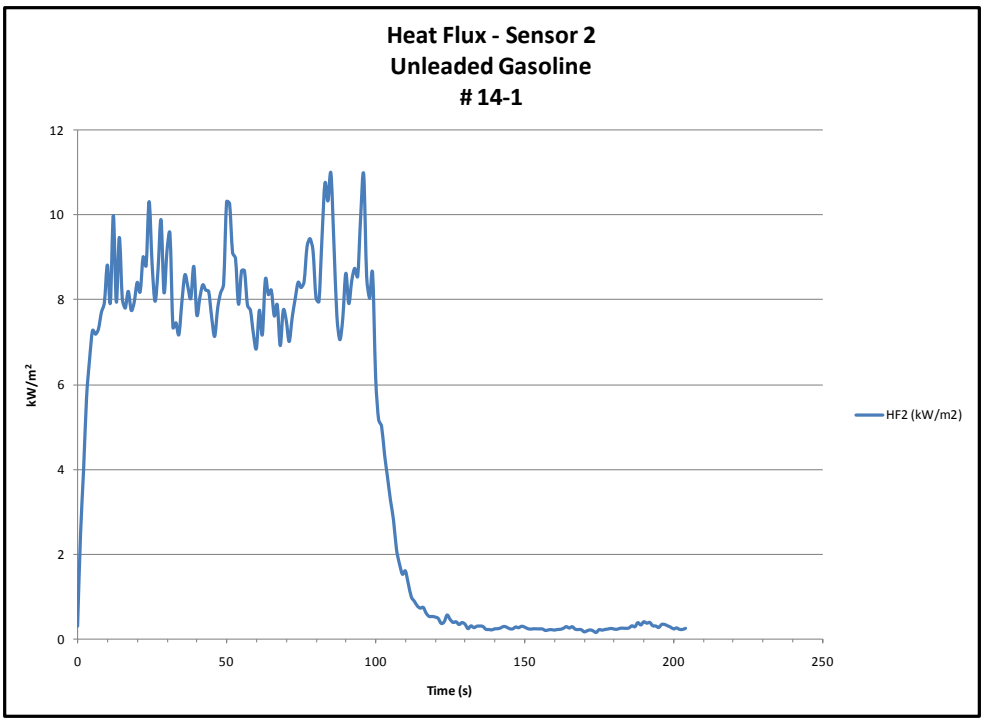

Distribution A: Approved for public release; distribution unlimited.

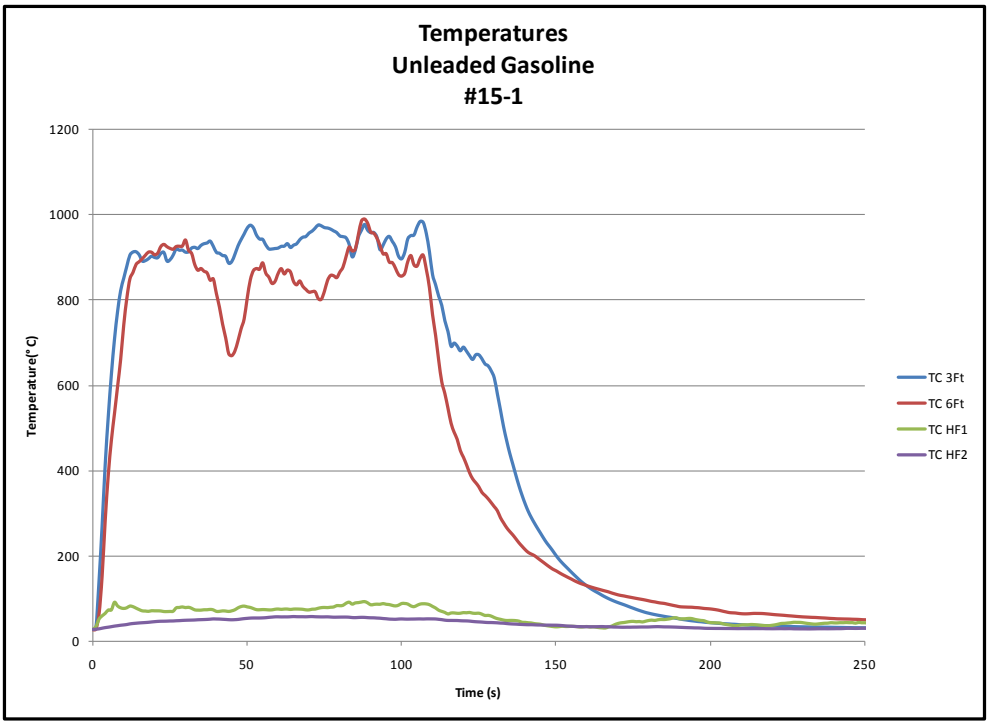
Appendix B: Unsuppressed Fuel Fire Data



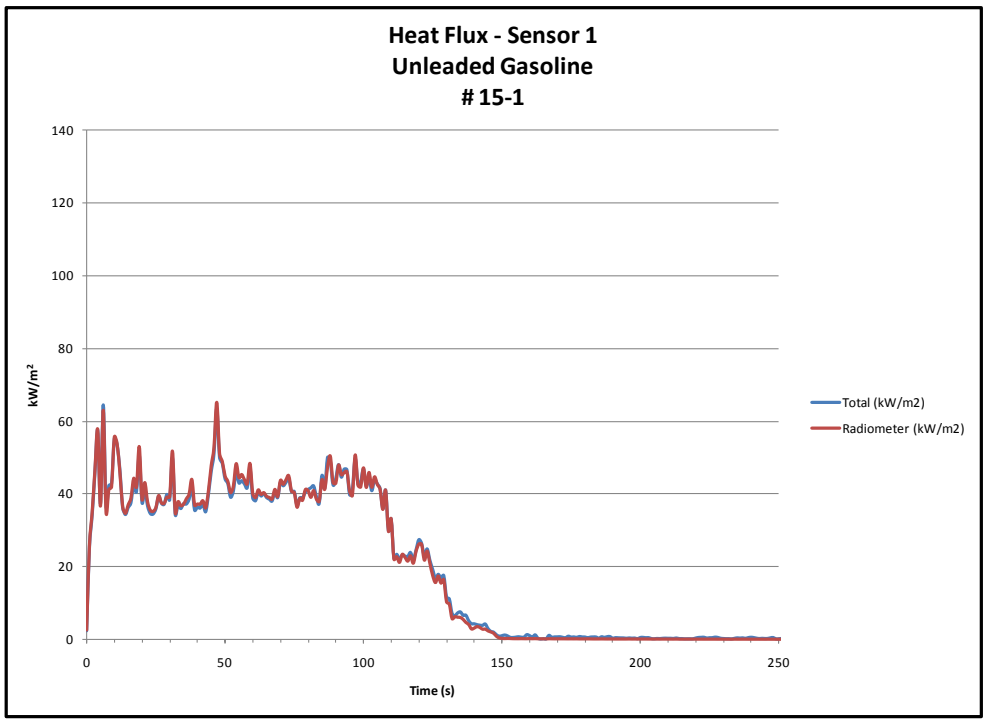


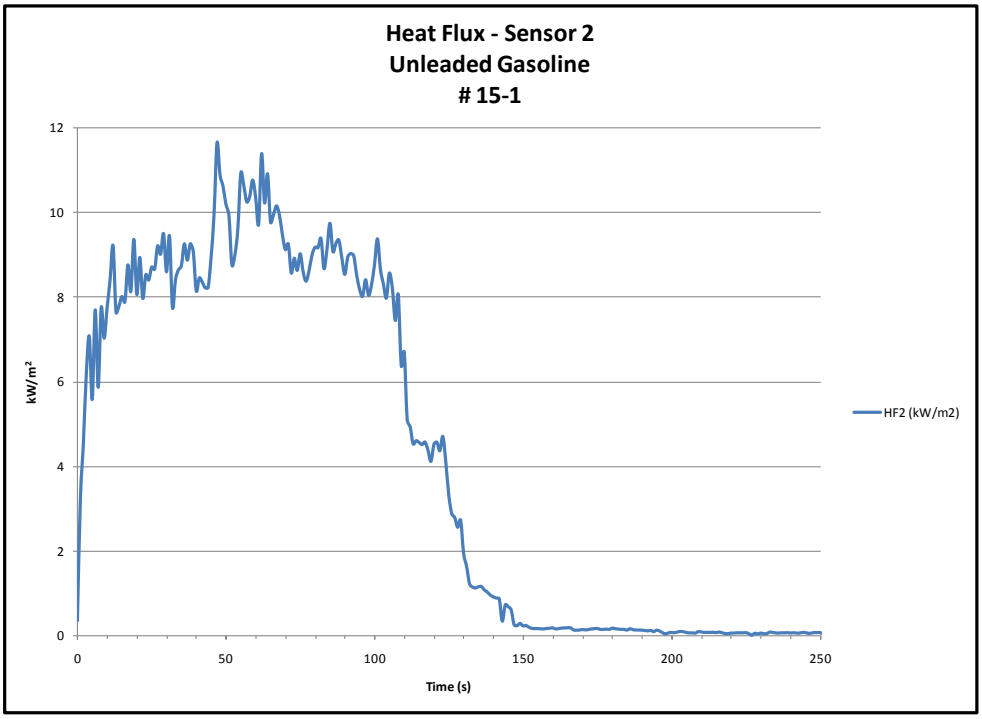
Distribution A: Approved for public release; distribution unlimited.



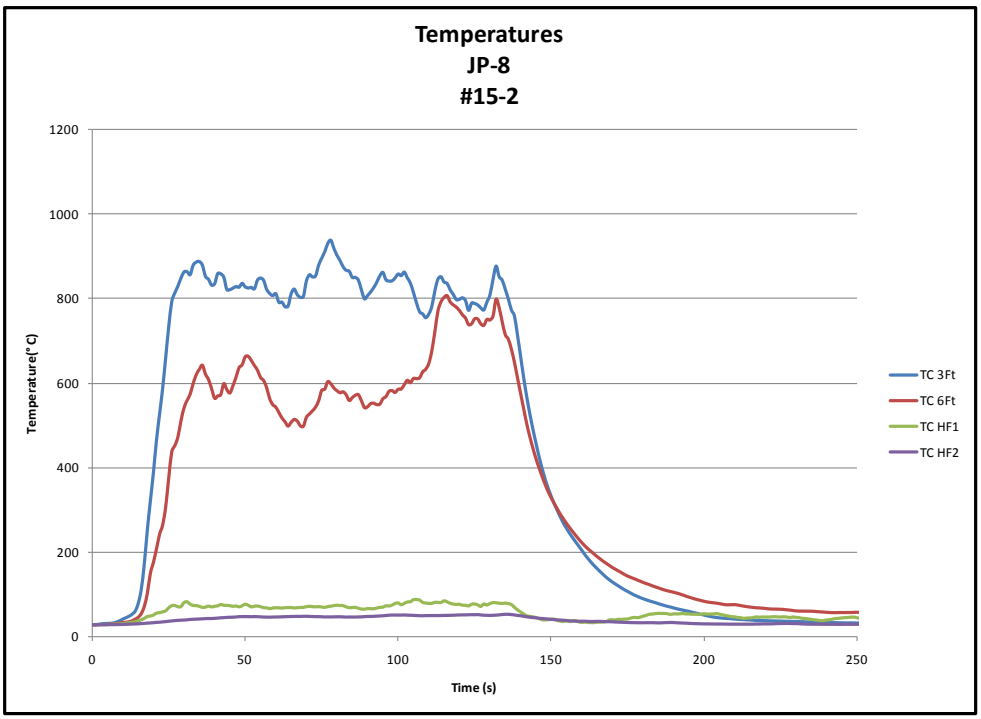


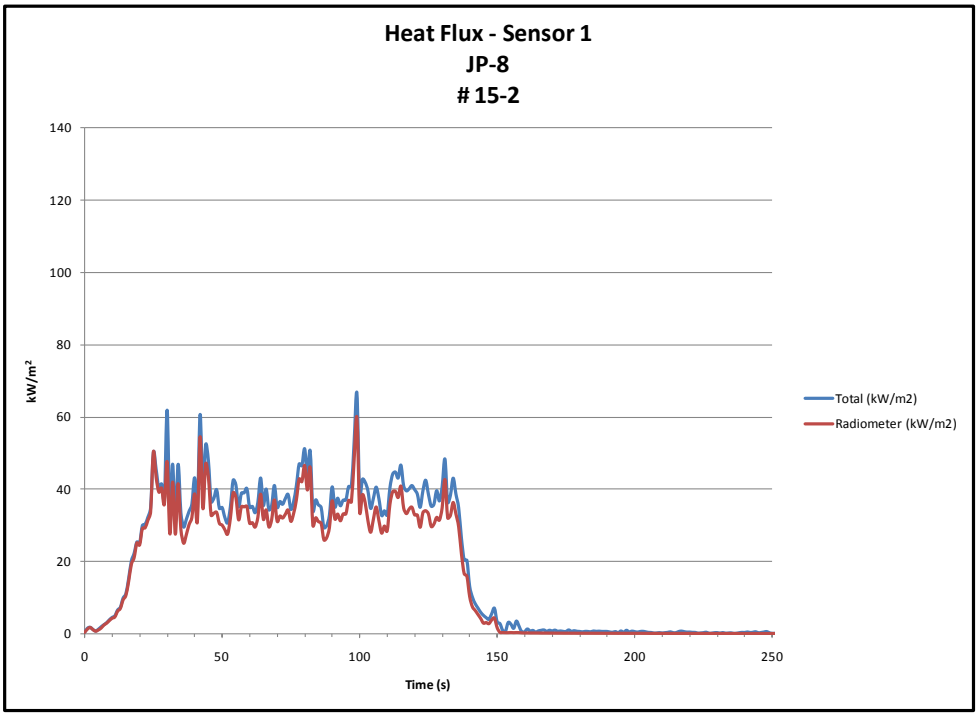
Distribution A: Approved for public release; distribution unlimited.



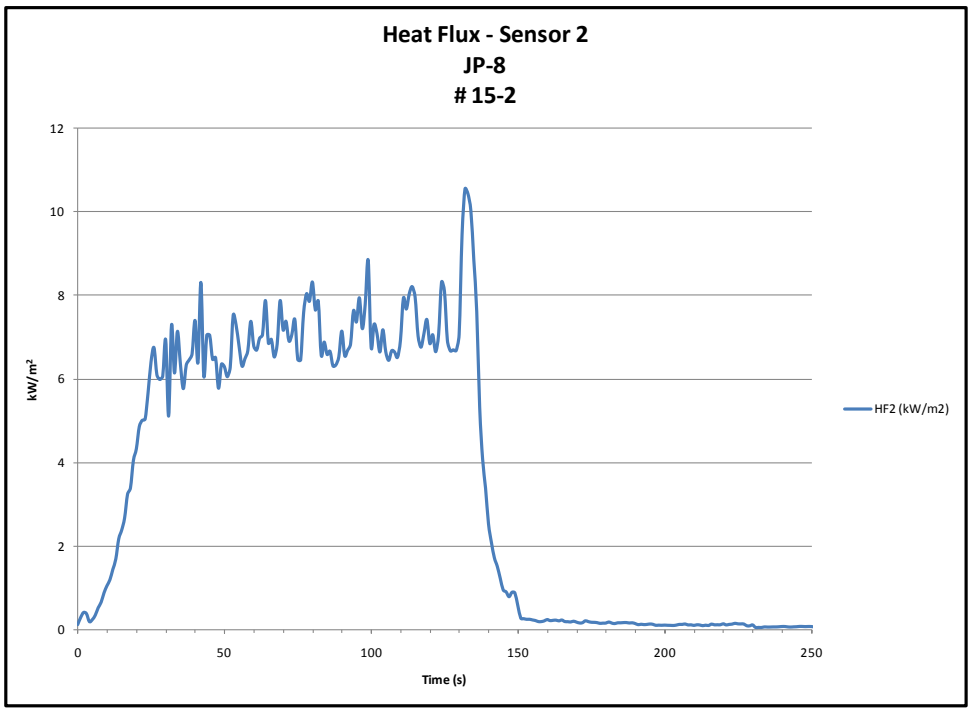


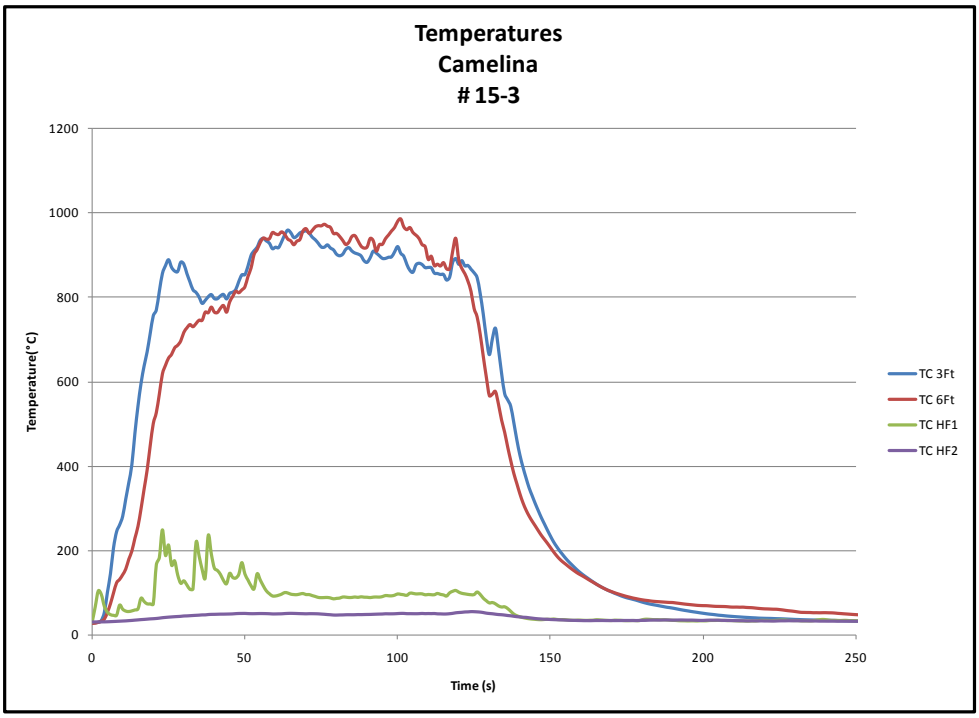
Distribution A: Approved for public release; distribution unlimited.



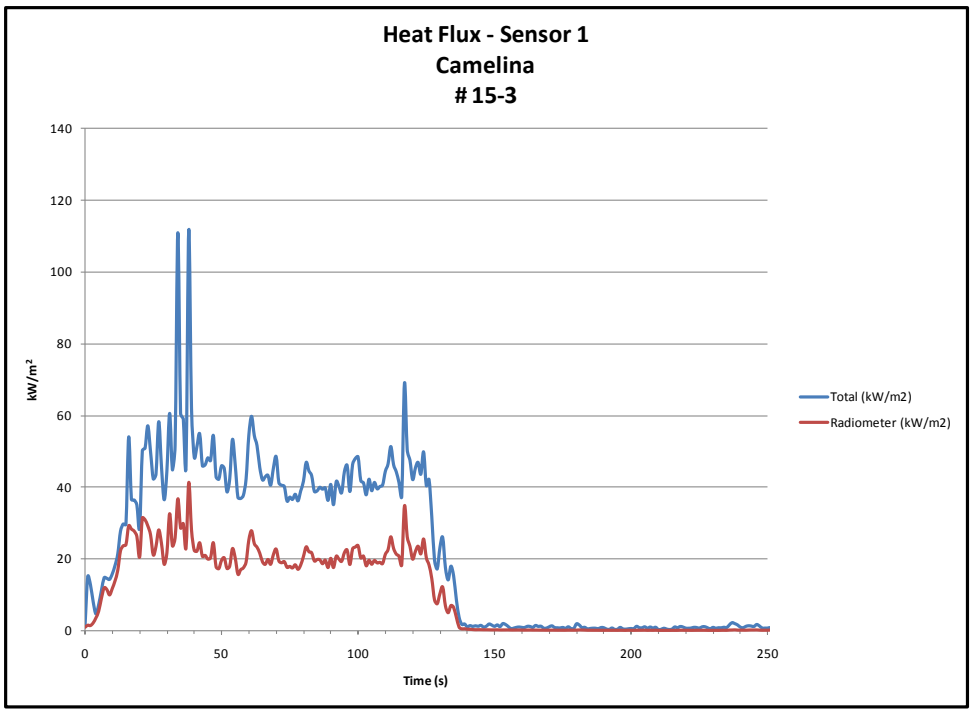


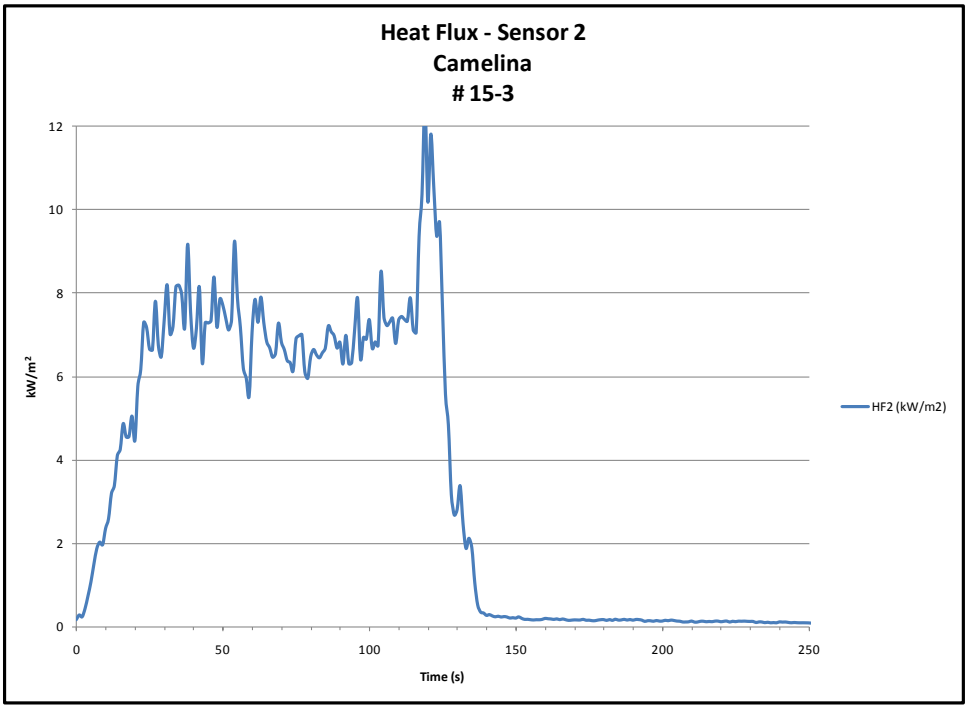
Distribution A: Approved for public release; distribution unlimited.



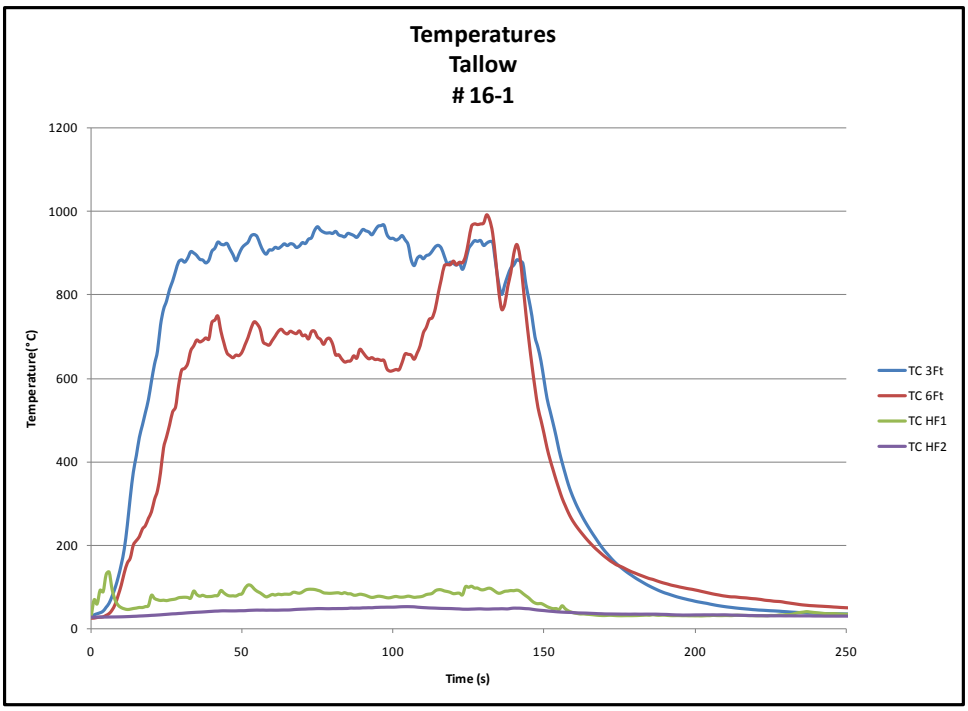


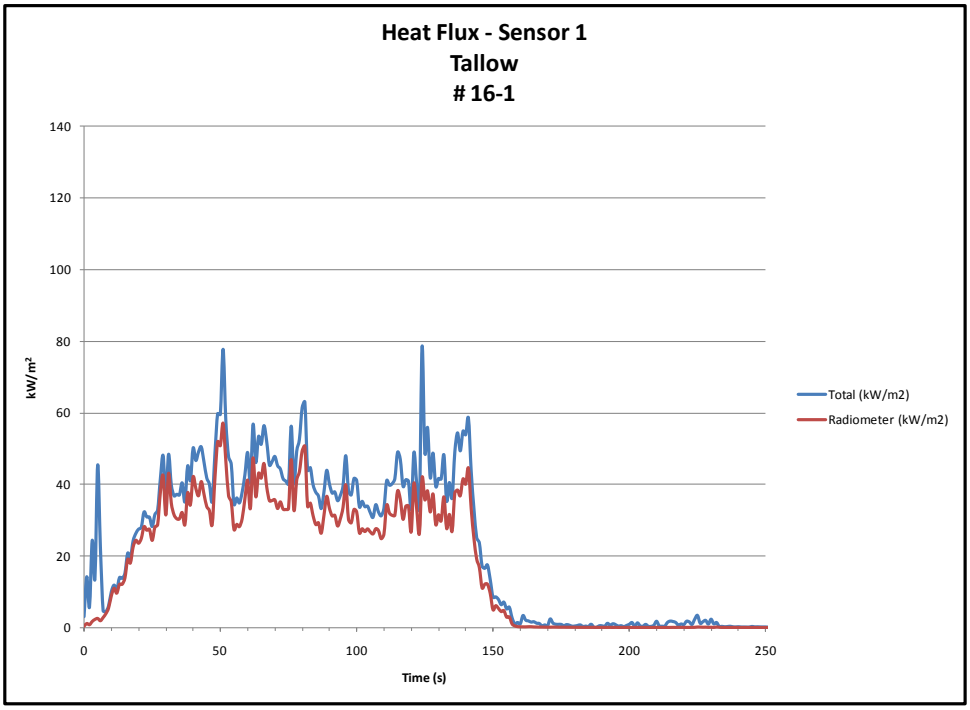
Distribution A: Approved for public release; distribution unlimited.



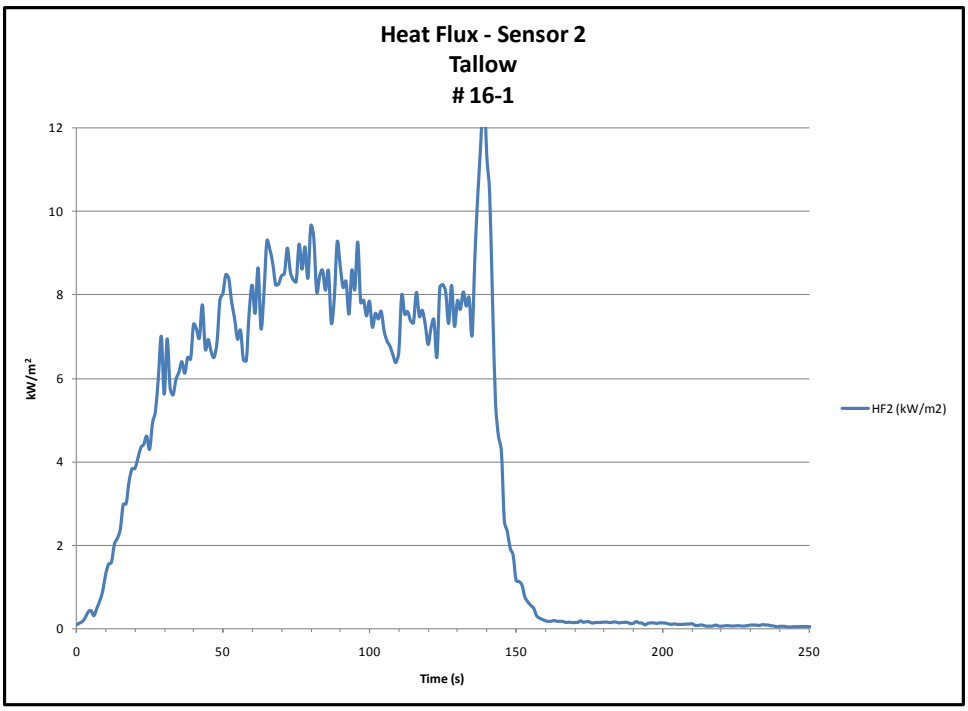


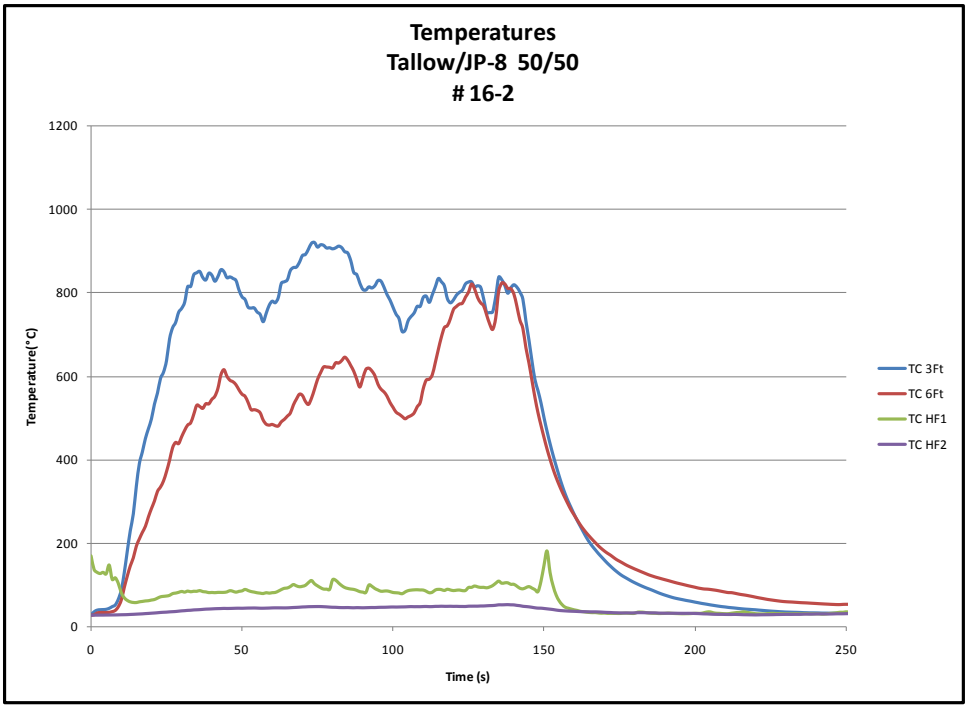
Distribution A: Approved for public release; distribution unlimited.



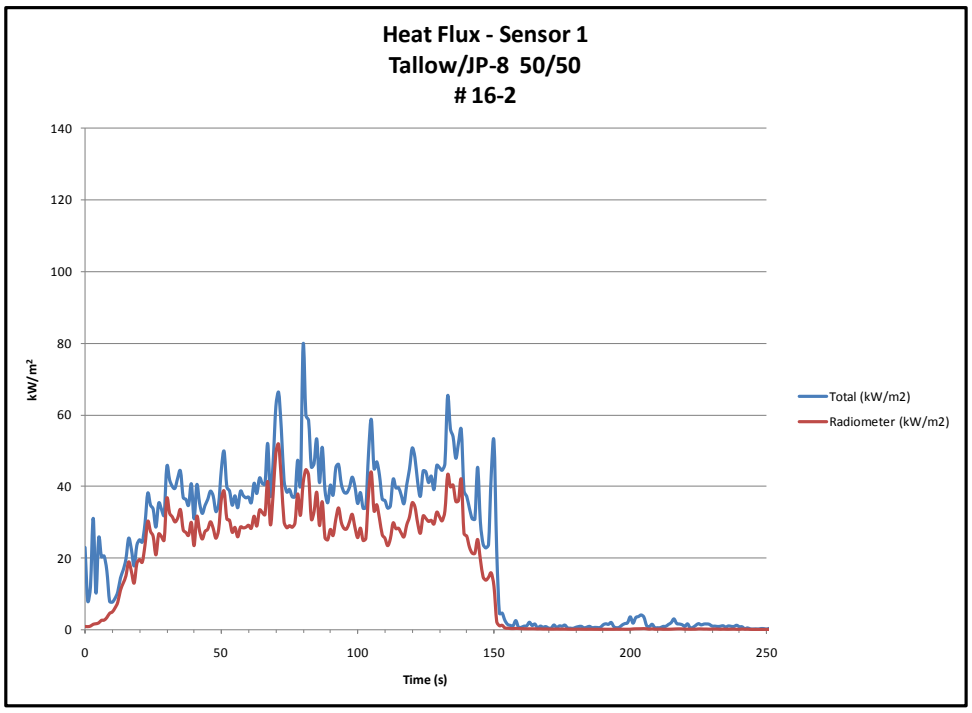


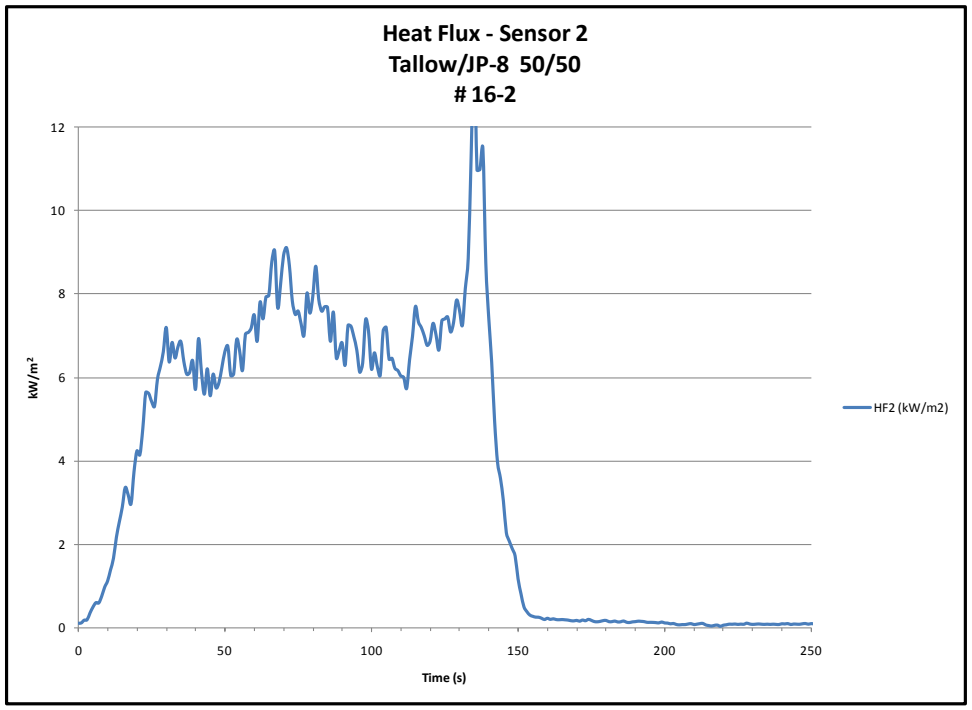
Distribution A: Approved for public release; distribution unlimited.



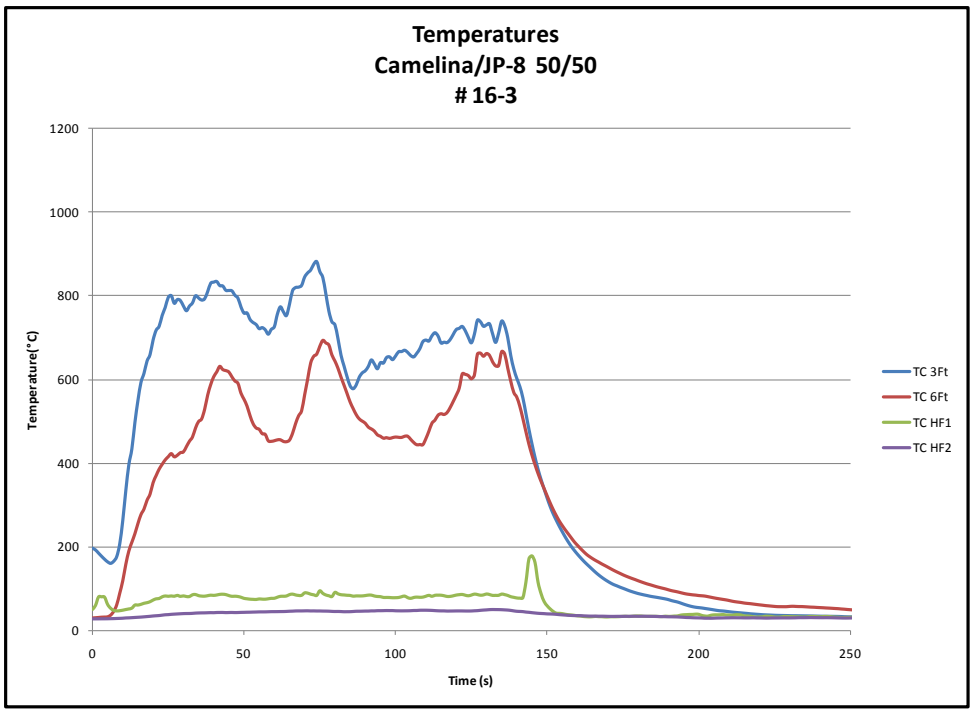


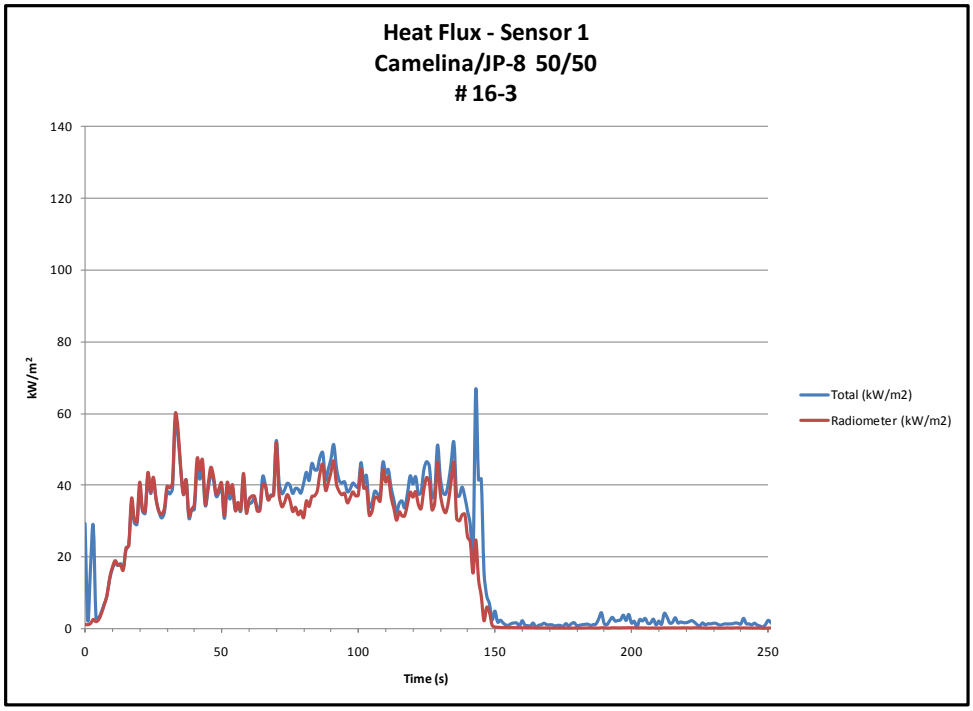
Distribution A: Approved for public release; distribution unlimited.



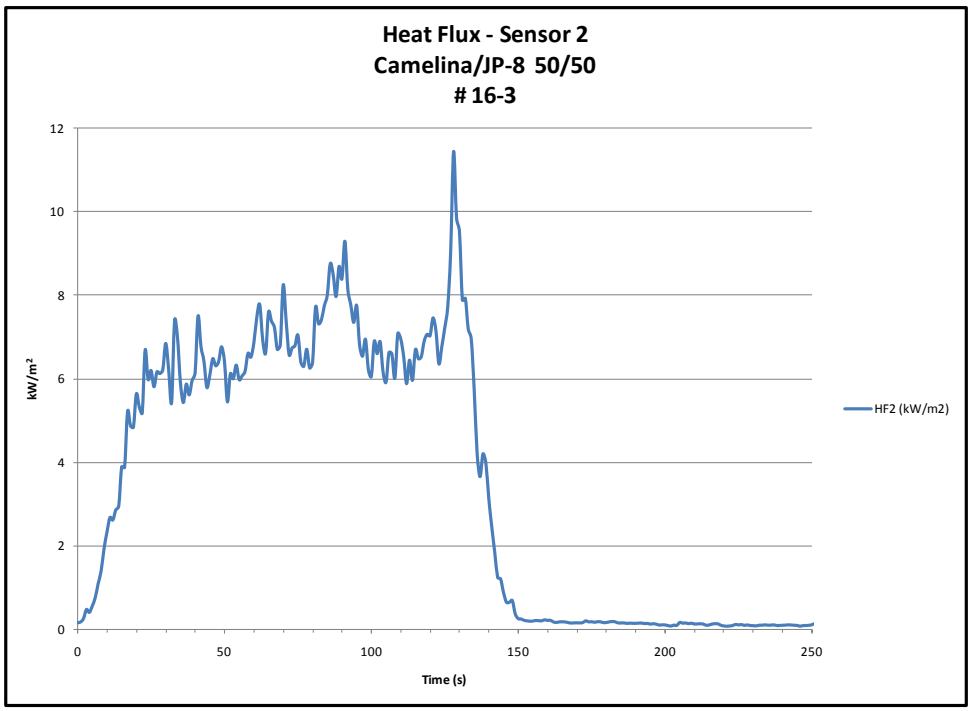


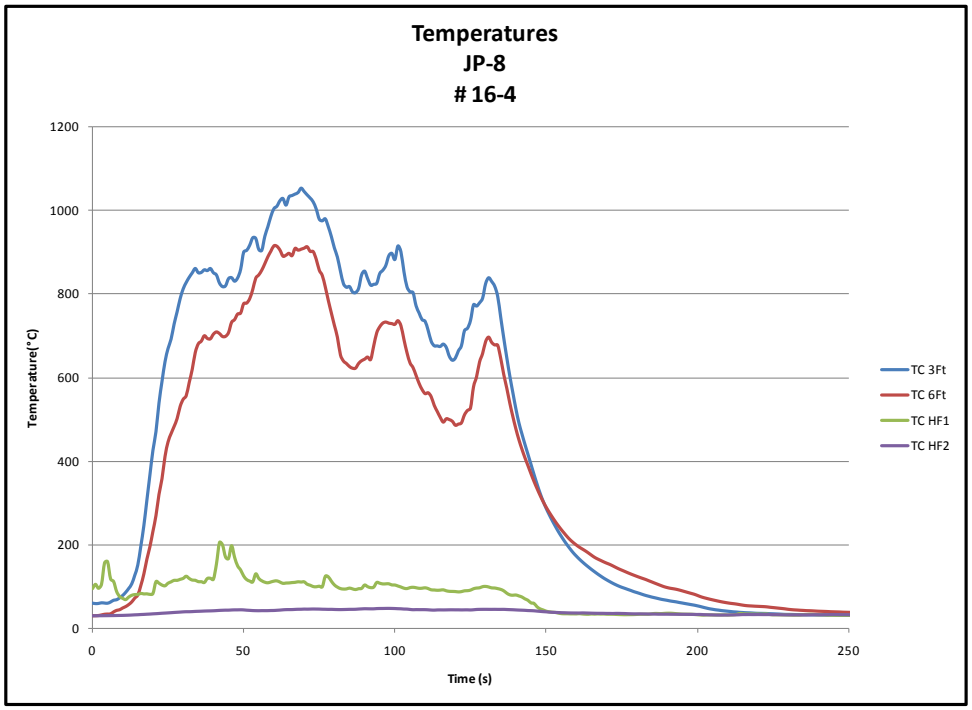
Distribution A: Approved for public release; distribution unlimited.



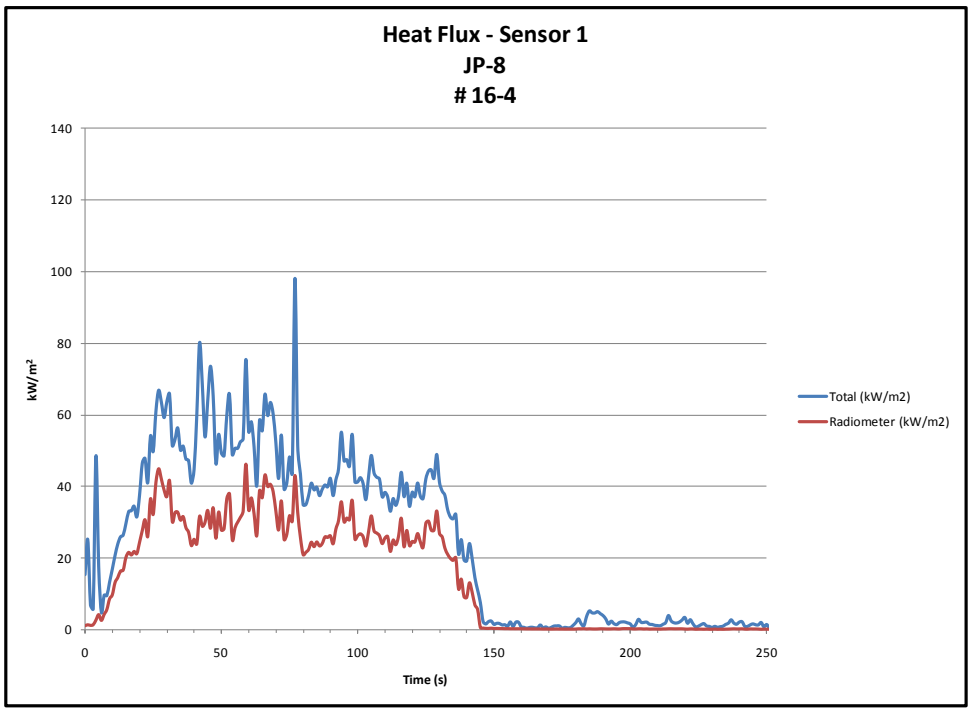


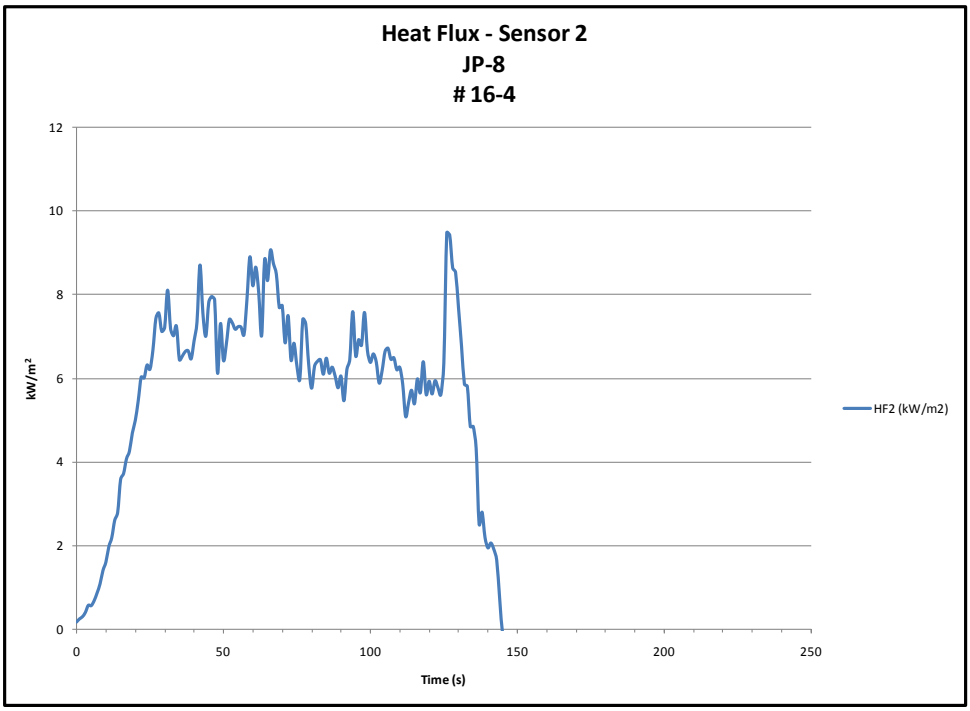
Distribution A: Approved for public release; distribution unlimited.



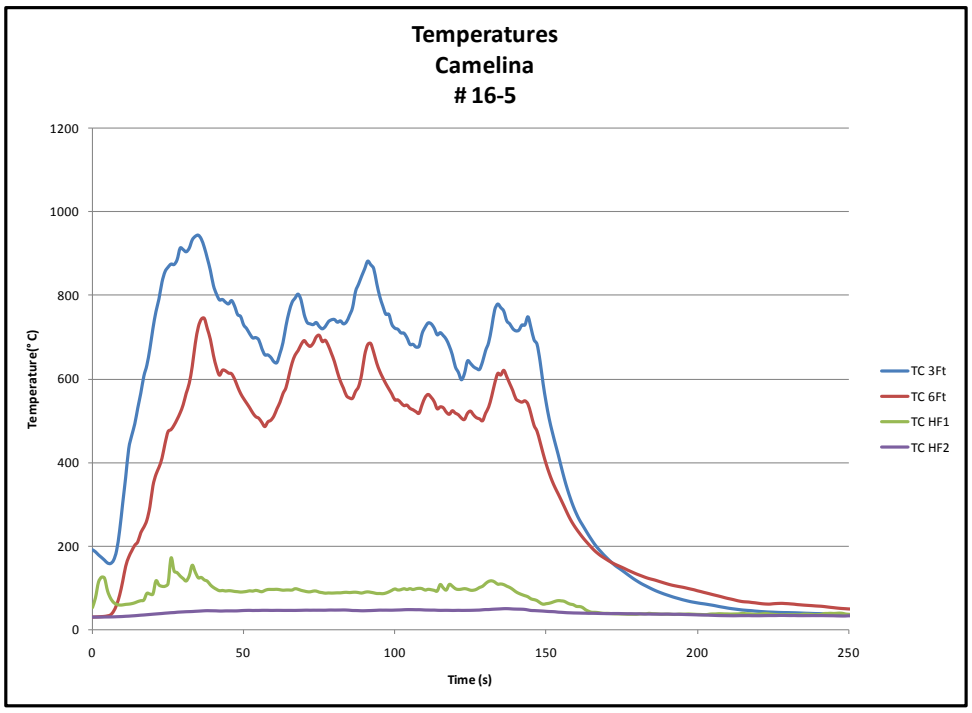


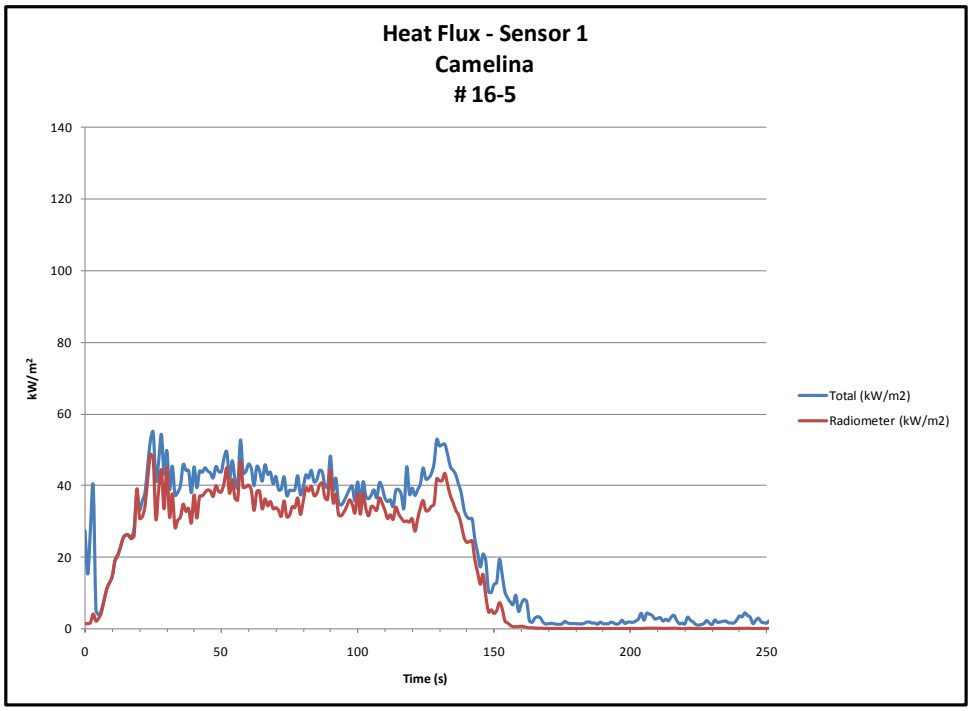
Distribution A: Approved for public release; distribution unlimited.



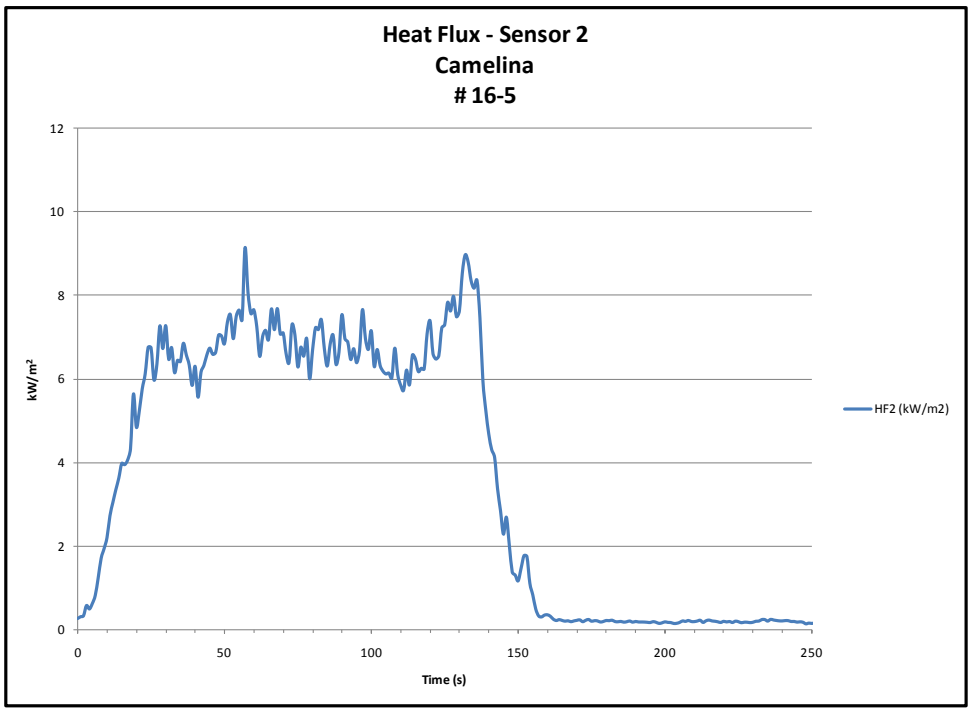


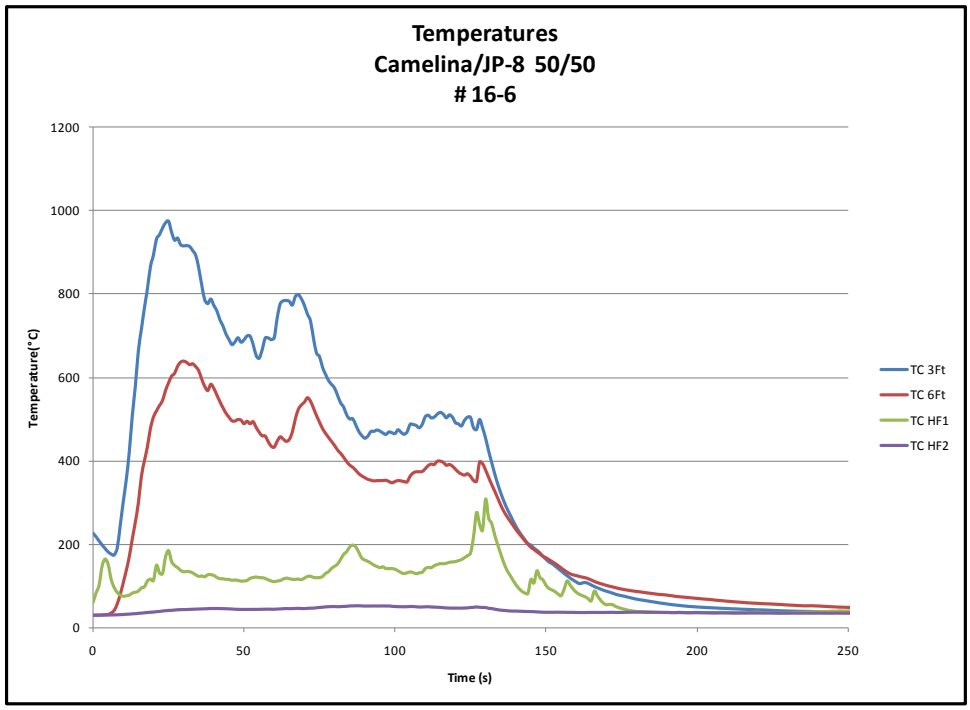
Distribution A: Approved for public release; distribution unlimited.



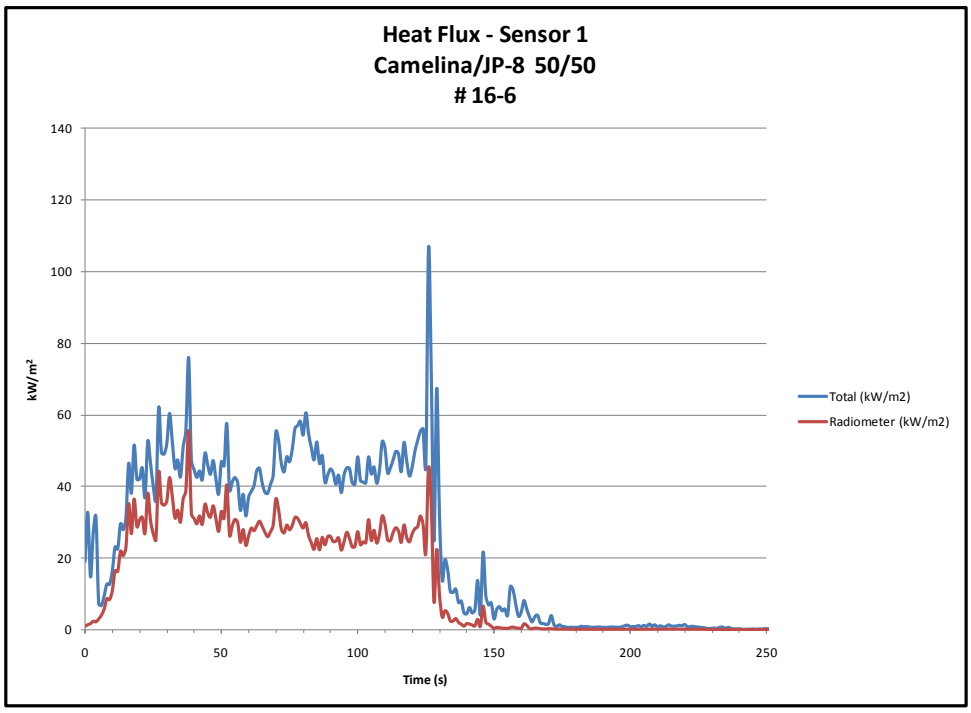


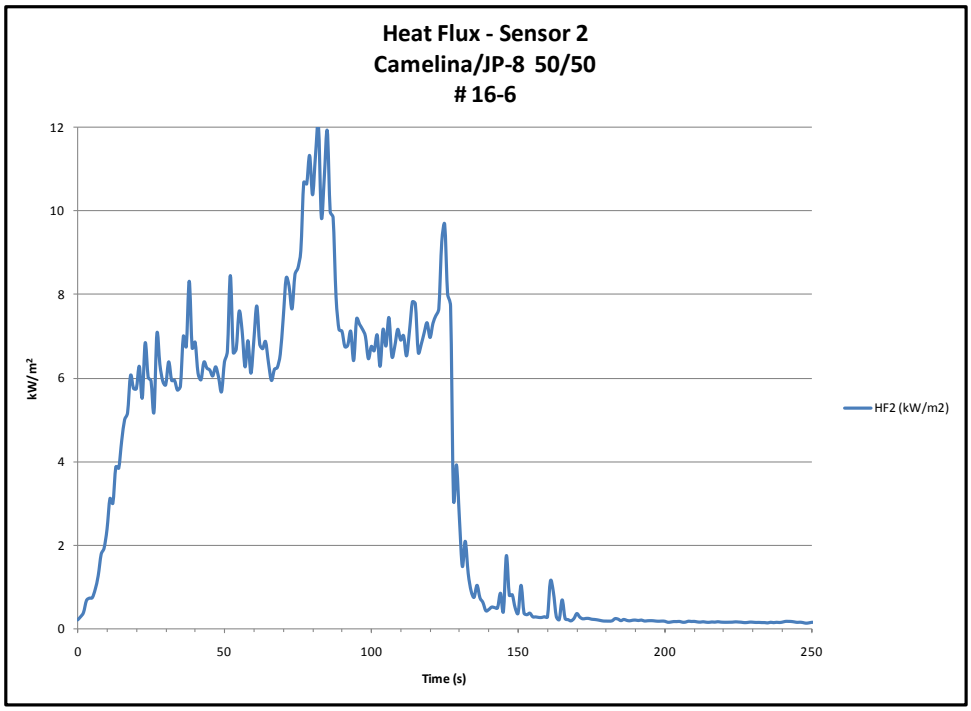
Distribution A: Approved for public release; distribution unlimited.



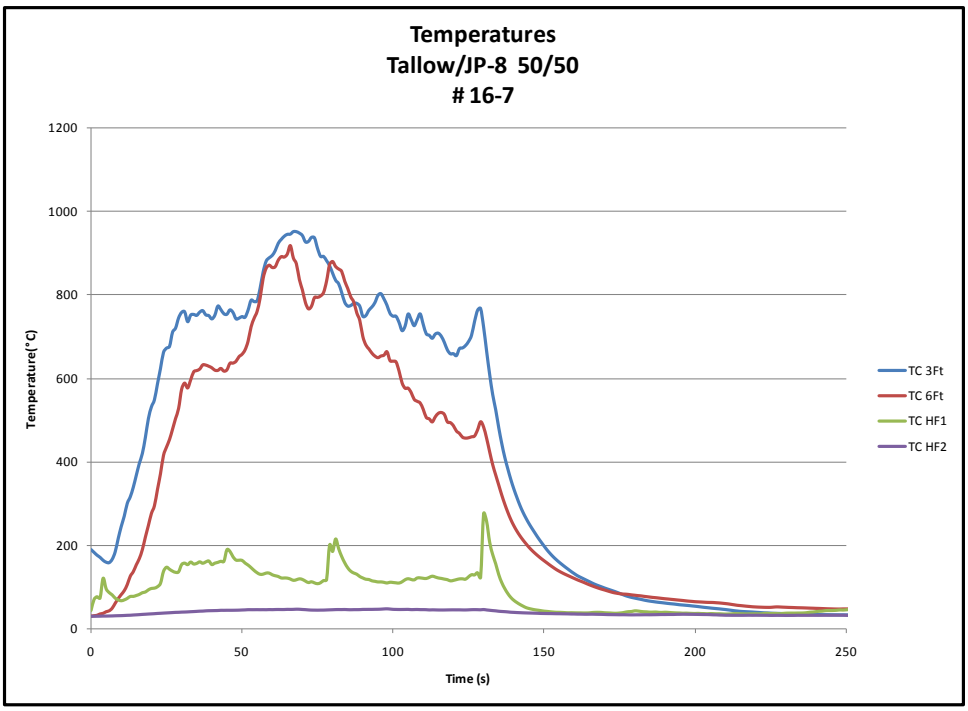


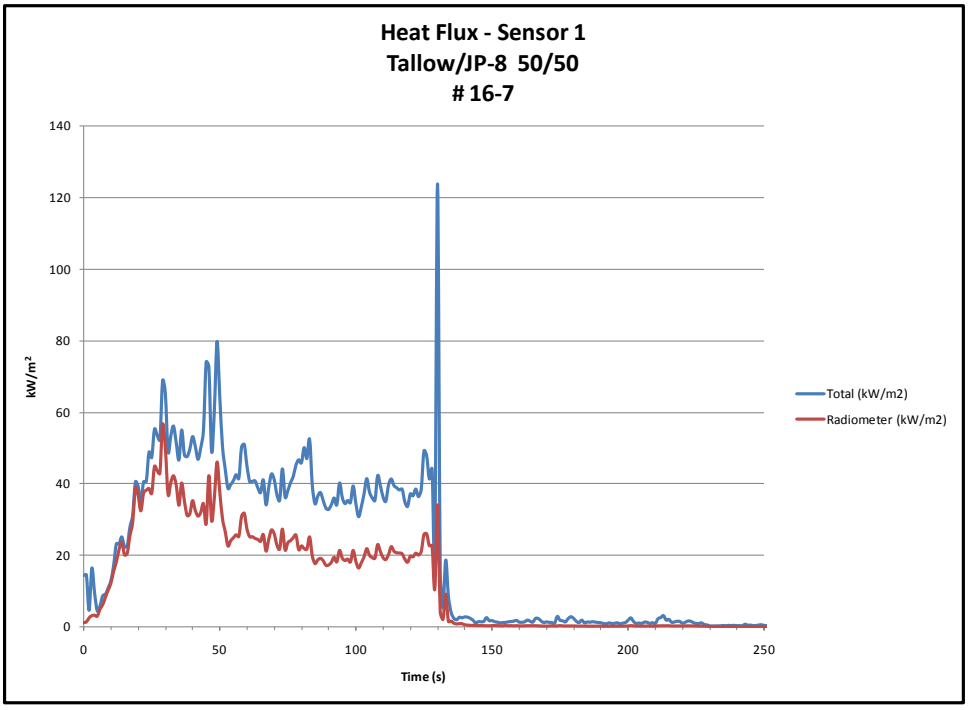
Distribution A: Approved for public release; distribution unlimited.



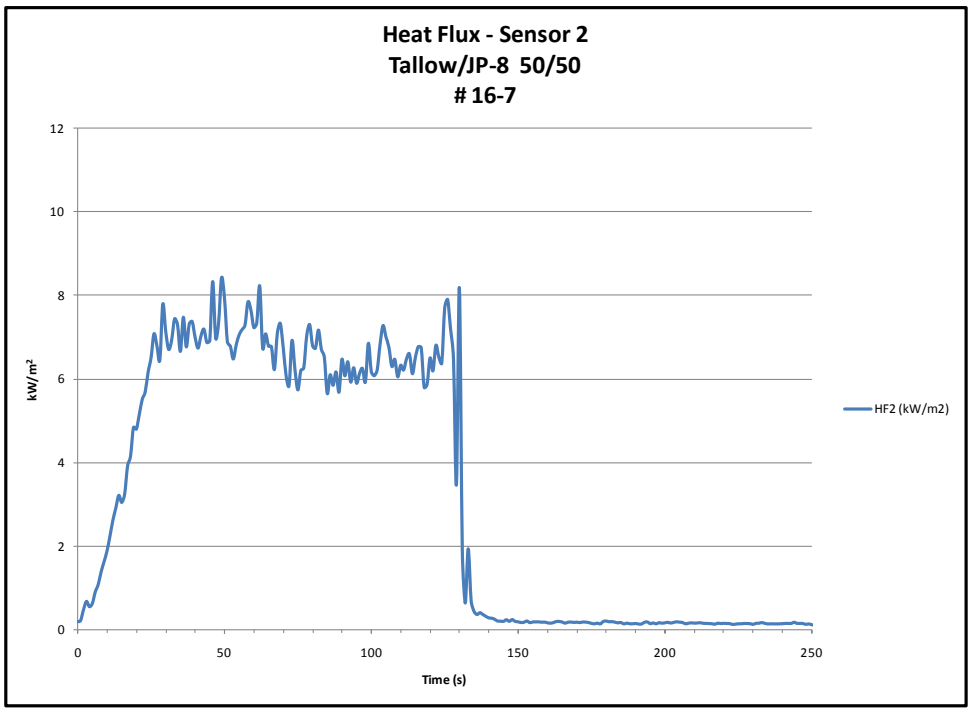


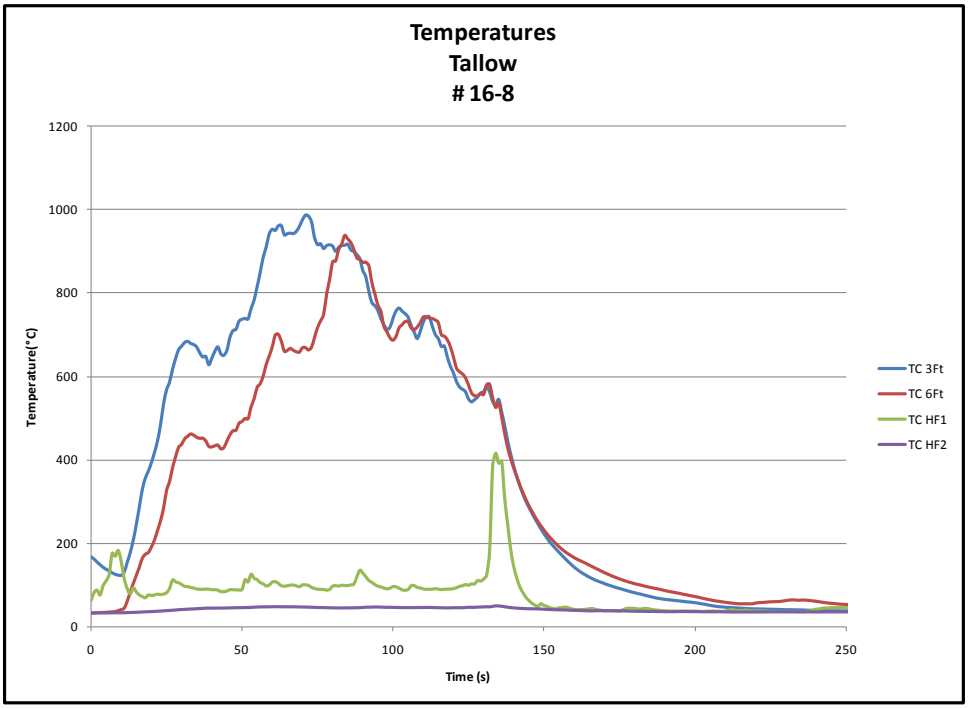
Distribution A: Approved for public release; distribution unlimited.



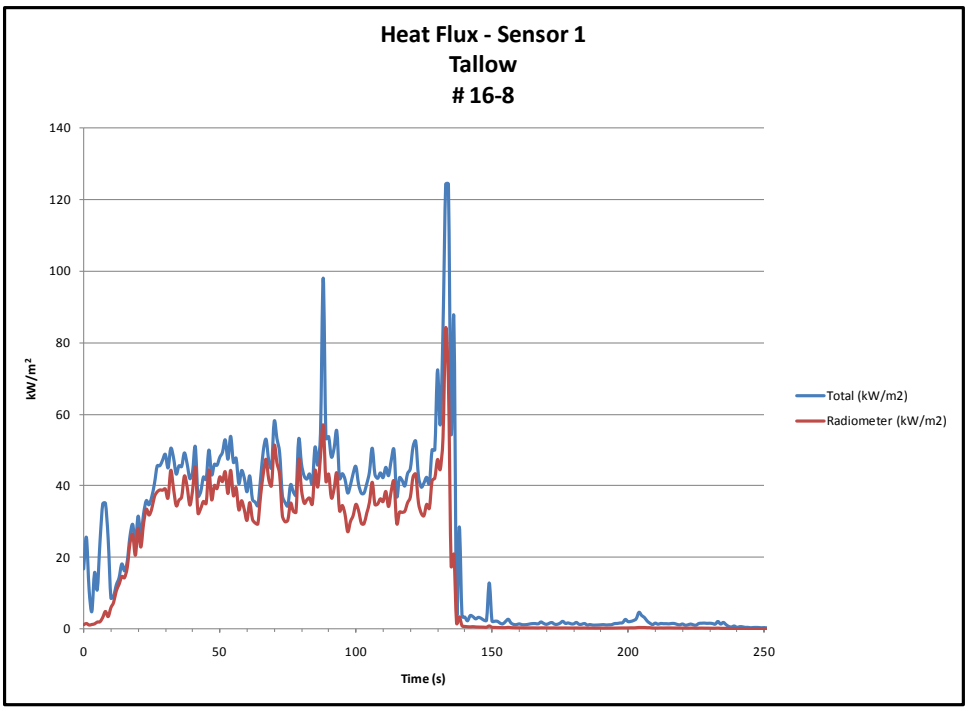


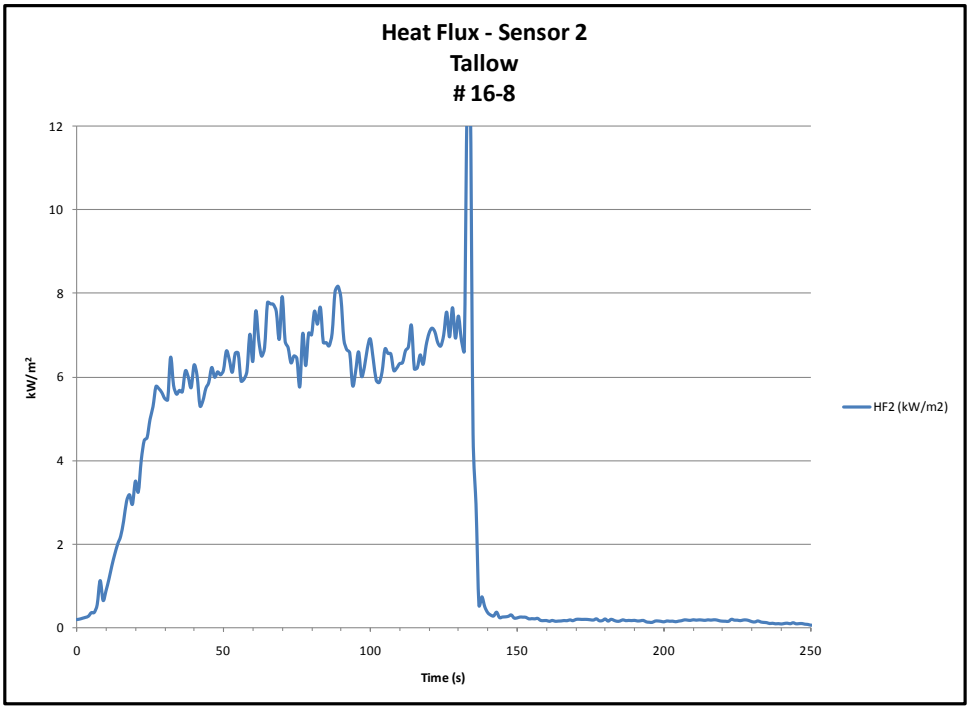
Distribution A: Approved for public release; distribution unlimited.



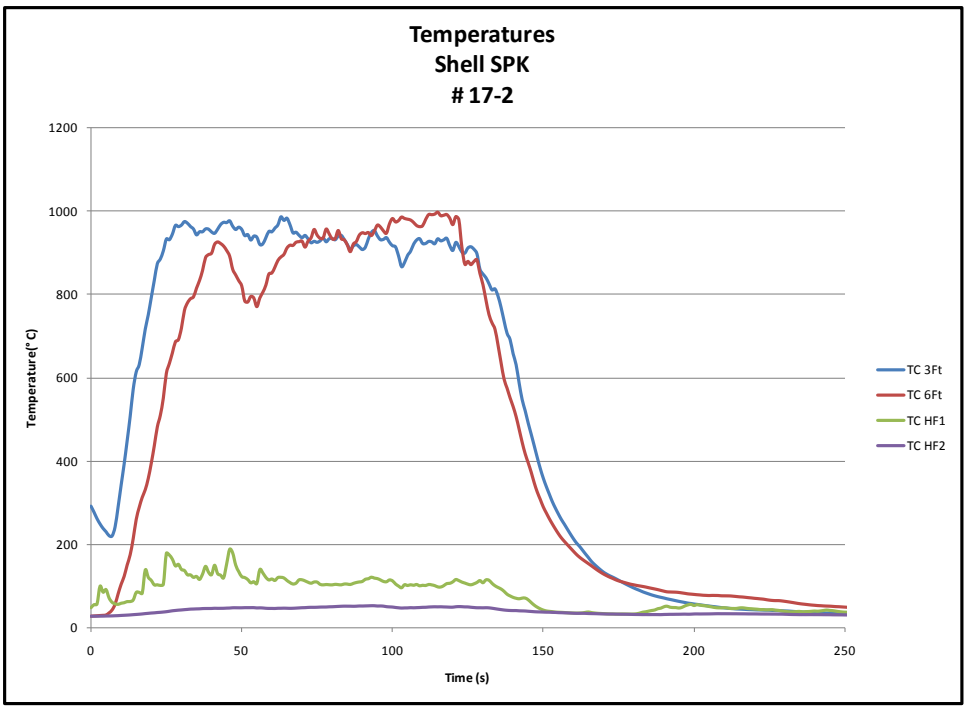


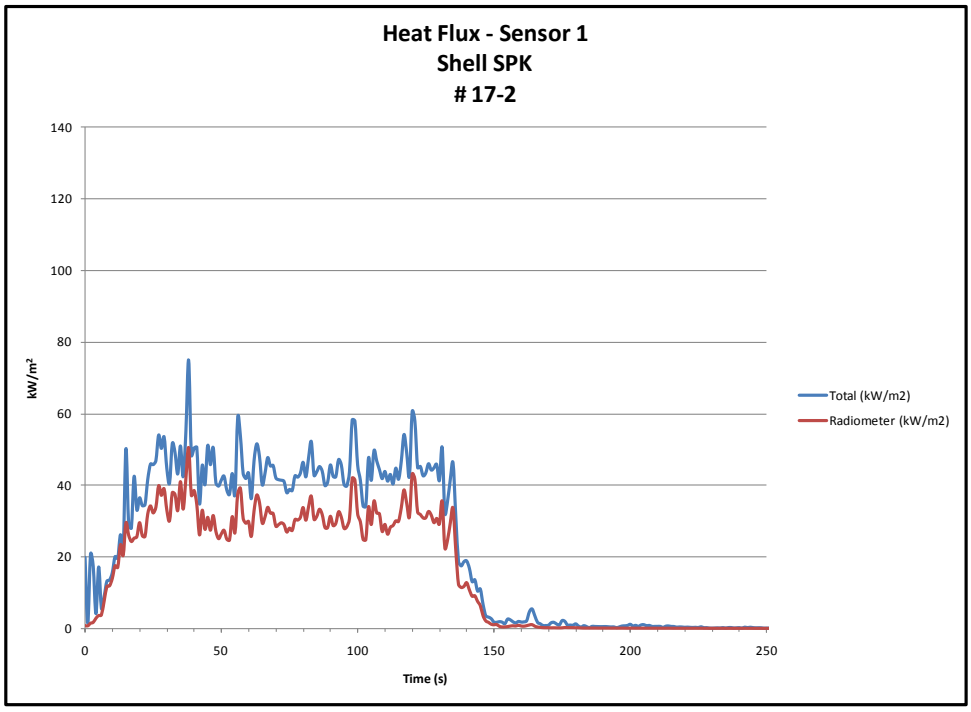
Distribution A: Approved for public release; distribution unlimited.



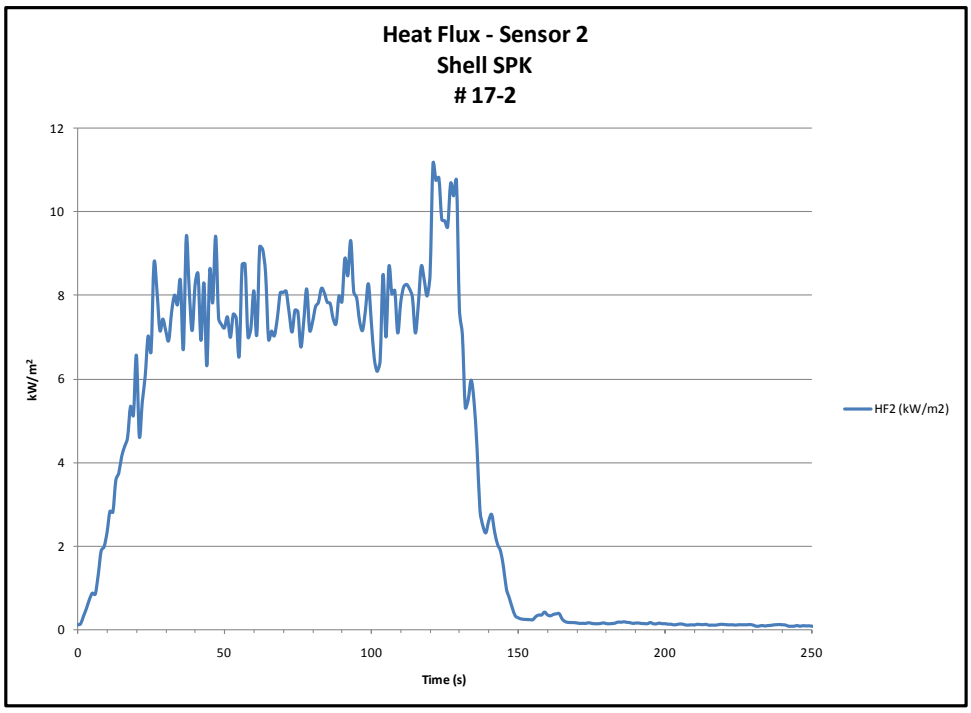


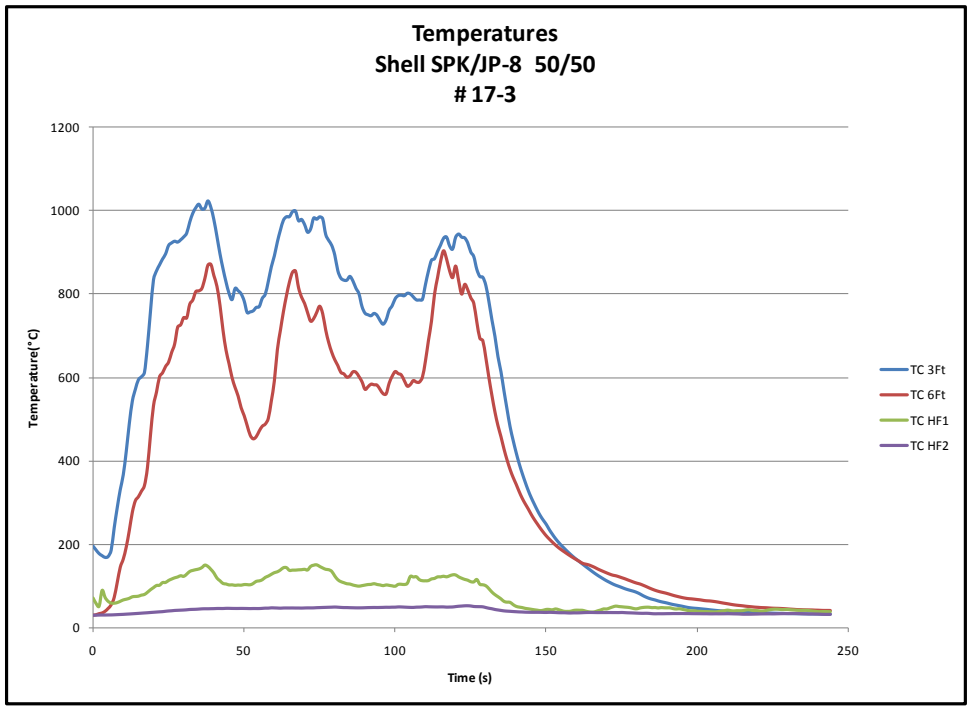
Distribution A: Approved for public release; distribution unlimited.



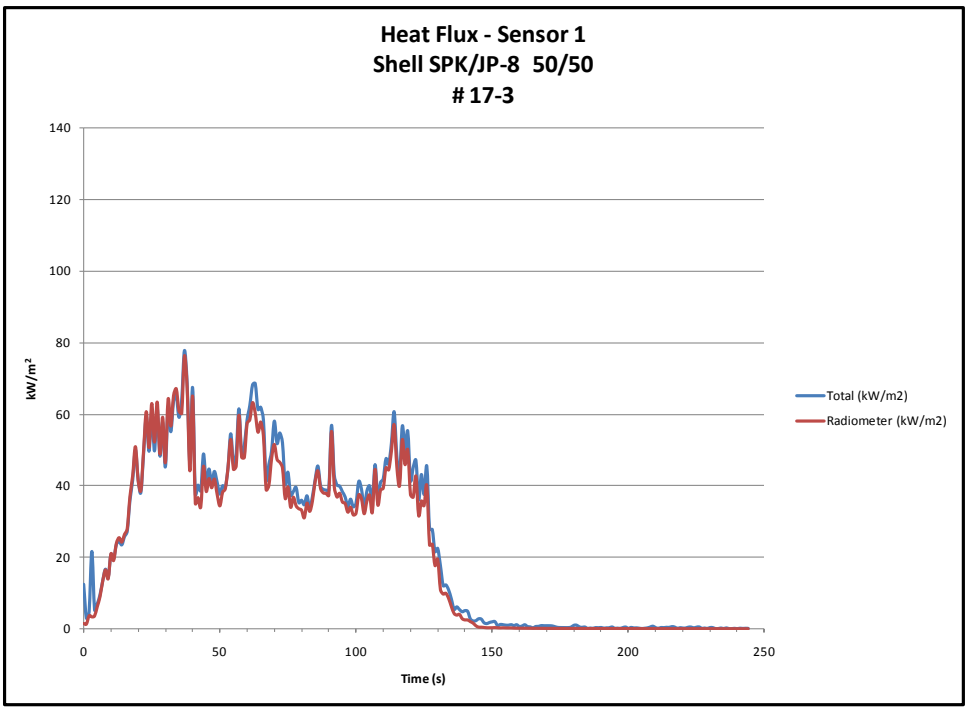


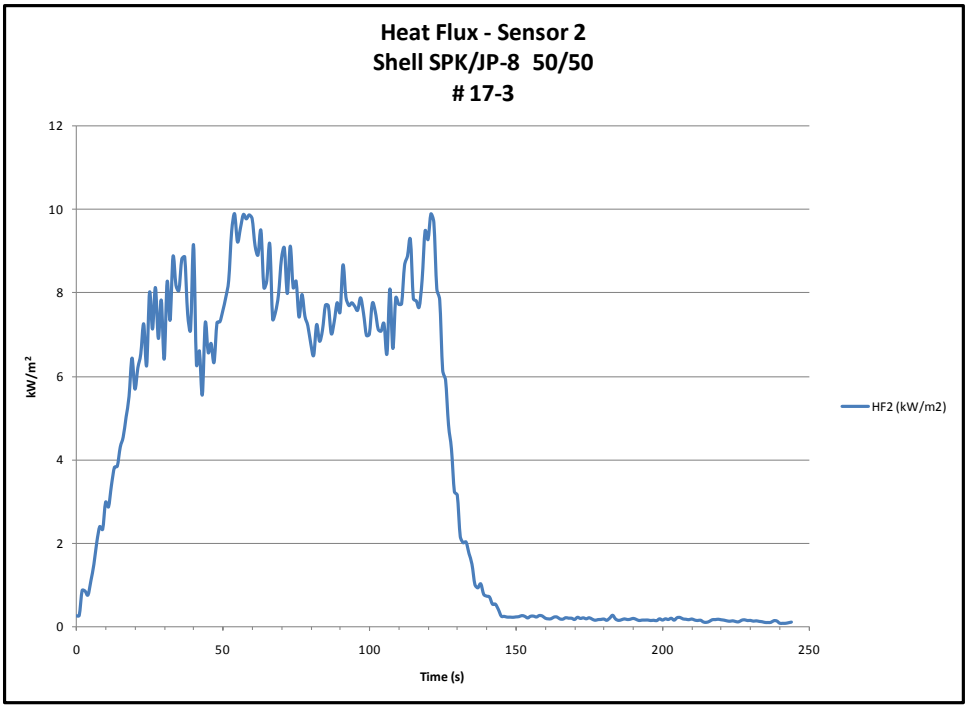
Distribution A: Approved for public release; distribution unlimited.



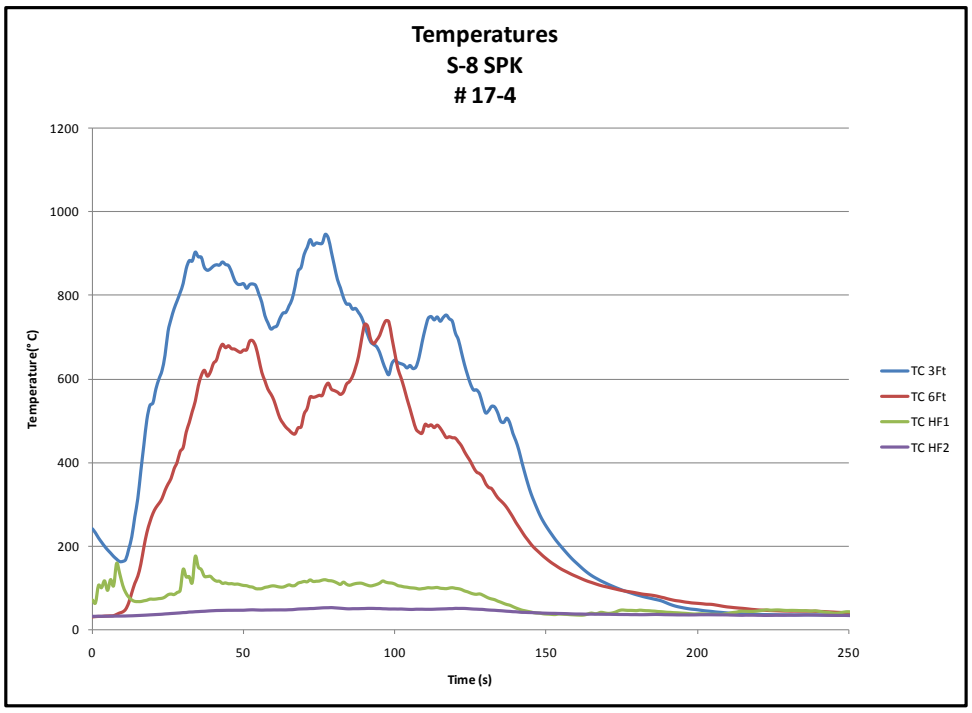


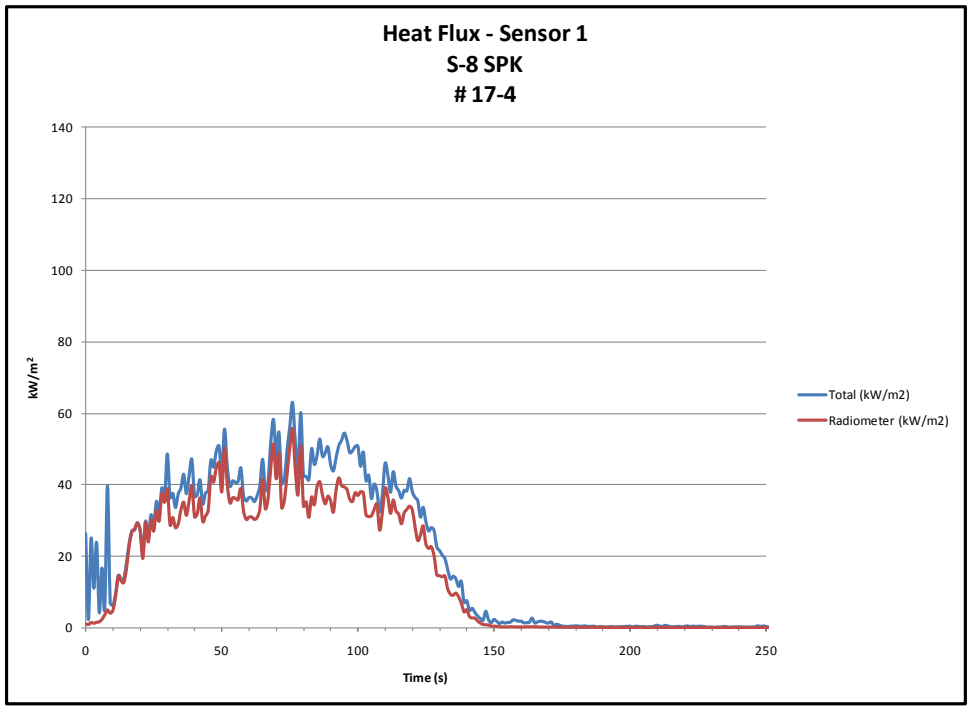
Distribution A: Approved for public release; distribution unlimited.



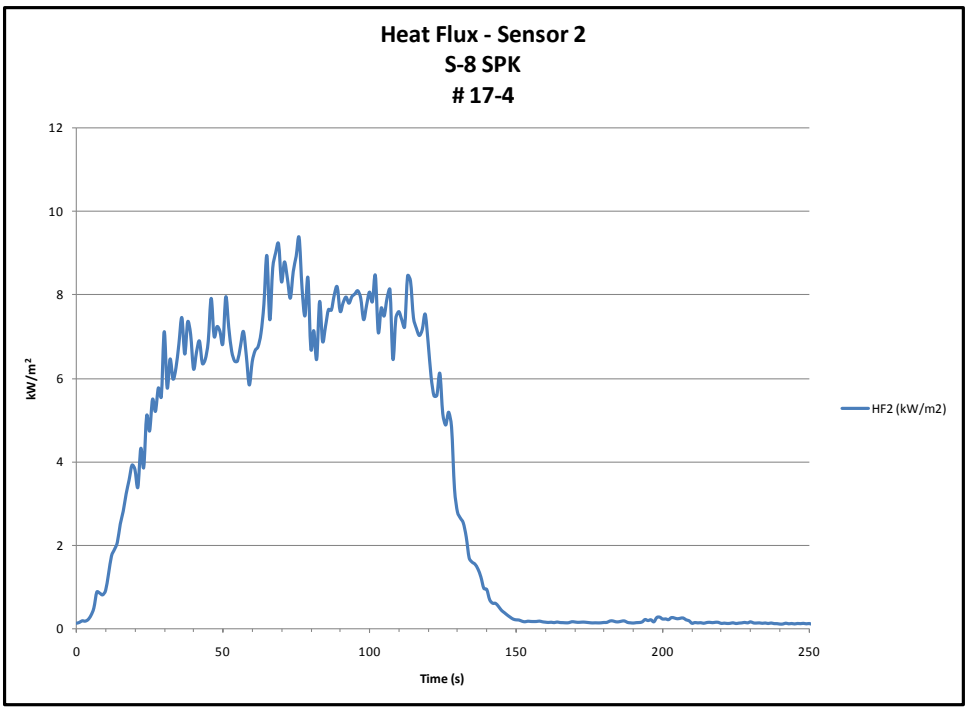


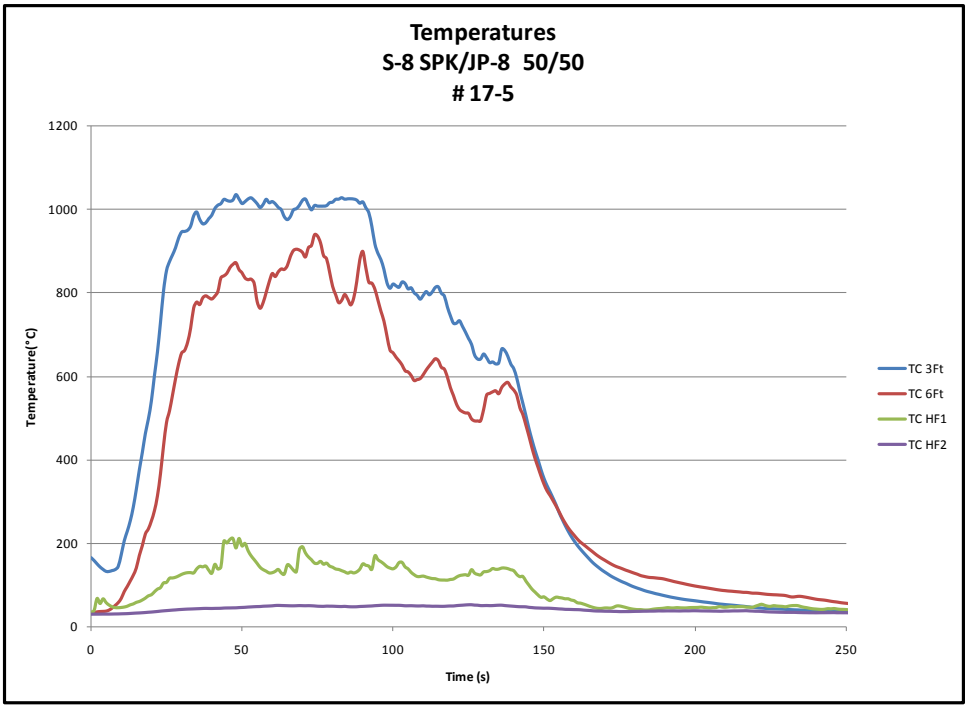
Distribution A: Approved for public release; distribution unlimited.



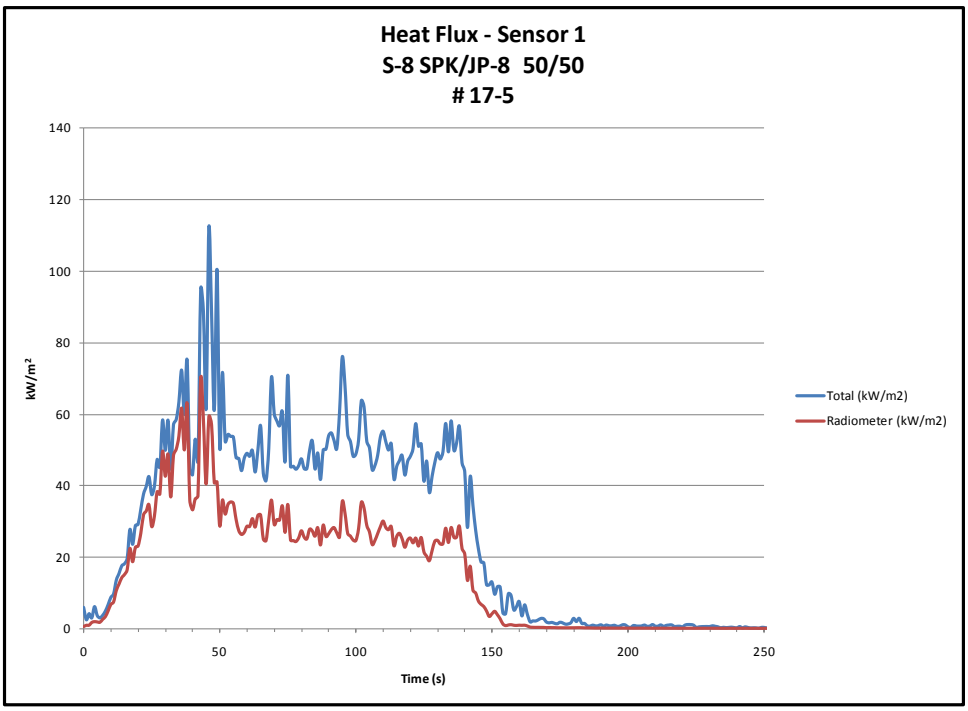


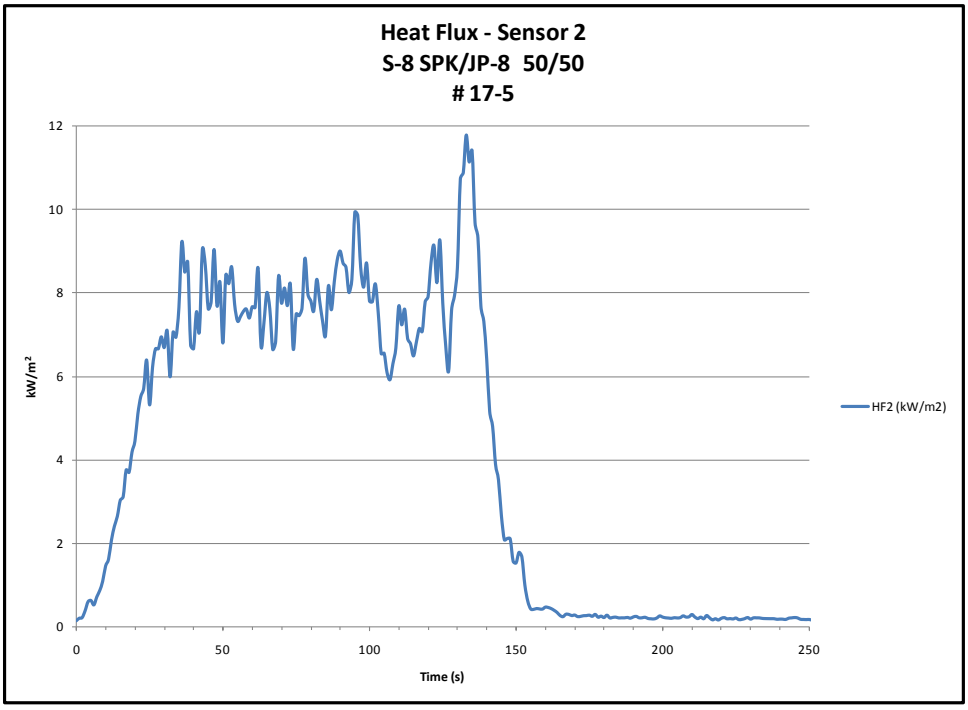
Distribution A: Approved for public release; distribution unlimited.





Distribution A: Approved for public release; distribution unlimited.





Distribution A: Approved for public release; distribution unlimited.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

50/50	a two-component mixture comprising equal volumes of the constituents
AFFF	Aqueous Film Forming Foam
AFRL	Air Force Research Laboratory
CI	confidence intervals
DF	degrees of freedom
ft^2	square feet
FT	Fischer–Tropsch
FT-IPK	Shell Oil SPK Fischer–Tropsch Iso-Paraffinic Kerosene
gal	gallons
HEFA	hydroprocessed esters and fatty acids
HRJ	hydroprocessed renewable jet fuel
in^2	square inches
JP-8	jet propellant 8, i.e. jet fuel
kW	kilowatts
m^2	square meters
Mil-Spec	Military Specification
min	minute
MSDS	Material Safety Data Sheet
p	probability
psi	pounds per square inch
SE&V	support equipment and vehicles
SPK	synthetic paraffinic kerosene
S-8	Syntroleum SPK jet fuel
s	seconds
t_{bb}	burn-back time
t_{ex}	extinguishment time
USAF	United States Air Force
°C	degrees Celsius
°F	degrees Fahrenheit

Distribution A: Approved for public release; distribution unlimited.